EuroGOOS Publication No. 9
May 1998
EG97.14

European Global Ocean Observing System

The EuroGOOS Atlantic Workshop Report

Published by:

EuroGOOS Office, Room 346/18
Southampton Oceanography Centre
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First published 1998

ISBN 0-904175-33-2

To be cited as:
Le Provost, C and N C Flemming (eds) (1998) "The EuroGOOS Atlantic Workshop Report", EuroGOOS Publication No. 9, Southampton Oceanography Centre, Southampton. ISBN 0-904175-33-2.

Cover picture

Large image: "A water perspective of Europe", courtesy of Swedish Meteorological and Hydrological Institute. The white lines show the watershed boundaries between the different catchment areas flowing into the regional seas of Europe.

Inset image: Height of the sea surface in the north Atlantic and Arctic simulated by the OCCAM global ocean model, courtesy of David Webb, James Rennell Division, Southampton Oceanography Centre.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
May 1998

3. REPORT TYPE AND DATES COVERED
30 - 31 Oct 1997

4. TITLE AND SUBTITLE
The EuroGOOS Atlantic Workshop Report
EuroGOOS Publication No. 9, May 1998
EG97.14

5. FUNDING NUMBERS
N00014-97-1-0538

6. AUTHOR(S)
Editors C Le Provost and N C Flemming

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
EuroGOOS Publication No. 9
May 1998
EG97.14

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Technical Director
Office of Naval Research International Field Office
PSC 802 Box 39
FPO AE 09499-0700

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release, distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

"The contents of this report provide an illustration of the state of the art in operational modelling on an ocean basin scale, and show the way forward for continued co-operation in measuring the oceanographic conditions in the Atlantic, and transmitting the data to real time operational models. The Report starts with the Chairman's Overview of the Workshop, followed by the conclusions of the 4 drafting groups which met during the Workshop, and then short summaries of the papers which were presented by the speakers."

14. SUBJECT TERMS
Forecasting, modelling, shelf edge, oceanic and bethnic biochemical parameters, Atlantic, Gulf Stream, meteorology

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

The EuroGOOS Atlantic Workshop Report

Southampton Oceanography Centre 30-31 October 1997

Edited by C Le Provost and N C Flemming

Sponsored by ONR Europe

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11.	Mediterranean Forecasting System report	ISBN 0-904175-35-9
12.	Requirements Survey analysis	ISBN 0-904175-36-7
13.	The EuroGOOS Technology Plan Working Group Report	ISBN 0-904175-37-5

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Preface and acknowledgements

The European Association for the Global Ocean Observing System (EuroGOOS) exists to maximise the benefits to Europe from operational oceanography within the framework of the Global Ocean Observing System (GOOS).

The EuroGOOS Workshop on Atlantic Operational Modelling and Forecasting was held at the Southampton Oceanography Centre on 30 and 31 October 1997.

Europe naturally has a strong interest in understanding and predicting the state of the Atlantic on all timescales from days to decades. The understanding and forecasts can be used to improve the efficiency, safety, and environmental management of a wide range of industries, services, and regulatory activities, such as ship-routeing, fisheries, offshore oil and gas exploitation, pipe-laying and cable-laying, recreational yachting, marine tourism, coastal defences against erosion and flooding, and response to climate variability, and climate change.

Operational oceanography in the European coastal and semi-enclosed seas can be developed by the collaboration of European agencies alone, or, in the case of the Mediterranean, with the collaboration of the relevant agencies in North African and Middle Eastern countries. In the case of the Atlantic it was natural that EuroGOOS should approach North American agencies with a view to conducting a joint assessment of the need for civilian operational modelling and forecasting. The US Office of Naval Research in Europe (ONREUR) offered support for the participation of non-Governmental US experts, and contributed towards the costs of running the meeting and publication of this report. This support is gratefully acknowledged.

The contents of this report provide an illustration of the state of the art in operational modelling on an ocean basin scale, and show the way forward for continued co-operation in measuring the oceanographic conditions in the Atlantic, and transmitting the data to real time operational models. The Report starts with the Chairman's Overview of the Workshop, followed by the conclusions of the 4 drafting groups which met during the Workshop, and then short summaries of the papers which were presented by the speakers.

Chairman's overview

In November 1995, in Dublin, EuroGOOS identified, as a major objective, the modelling and forecasting of the state of the Atlantic in order to produce economic and social benefits for Europe, and the design of a European contribution to global ocean observation experiments such as the Global Ocean Data Assimilation Experiment (GODAE). In December 1996, at the Annual EuroGOOS Meeting, it was agreed that a Workshop will be held on the civil operational modelling of the Atlantic. Having concentrated the efforts of the Members of EuroGOOS on identifying the priorities and benefits from modelling the European coastal seas and the Mediterranean during the previous year, it was effectively urgent to start to identify the European priorities for operational modelling in the Atlantic.

The objective of the workshop was to build upon the research completed, or already planned, and on the experience of operational systems already in place, so as to identify and prioritise developments in operational modelling and forecasting in the Atlantic which will maximise the economic and social benefits to Europe. The workshop focused on physical oceanography but some attention was paid to biological oceanography. It was a priori noticed that Atlantic modelling and forecasting products with economic and social benefits include:

a) - Forecasts of surface and near surface sea state for oceanic shipping,
- forecasts of upper ocean conditions for fisheries management,
- monitoring and forecast of sea ice and icebergs,
- improved marine meteorology.

b) - Provision of oceanic boundary conditions for operational shelf seas models,
- forecasts of shelf edge and slope processes, needed by deep offshore oil producers,
- prediction of shelf edge and slope conditions relevant to fish stock migration,
- modelling and forecasting the dispersion and transport of oceanic contaminants and pollutants.

c) - Monitoring and predicting fluctuations in the Gulf Stream and the North Atlantic Current,
- monitoring and modelling the formation of Atlantic bottom water, the ventilation, convection, and deep water formation, the multi-annual and decadal changes of the state of the AO.

d) - Coupled ocean atmosphere forecasts of weather and European climate variability.
- seasonal and inter-annual forecasts for improving the management of agriculture, power generation, and fresh water.

e) - Assessment of oceanic and benthic biochemical parameters,
- modelling and predicting oceanic and global carbon transports and greenhouse gases.

It was also noted that the North Atlantic offers specific interests and advantages:

- From the physical point of view, long term forecast needs to consider the deep water formation processes, and deep ocean circulation. One key question addressed during the workshop was thus: should we focus first on the surface forecast, or should we consider immediately the deep waters too?

- From the observational point of view, this basin offers the availability of the largest amount of data. Especially floats will be in place during the coming years. There is thus in the Atlantic a unique opportunity to use these data, and demonstrate their usefulness for ocean forecasting. This will

help to ensure their continuation on the long term which is of major concern for the continuation of operational satellite observing systems, for the maintenance of the existing *in situ* ocean observing networks, and for the demonstration of the need for new observing systems and their design. It was also recognised that any action towards this goal of forecasting needs to be a joint venture with US, Canada, and other countries from the two sides of the Atlantic Ocean.

The workshop followed immediately after a workshop in Portsmouth on naval oceanographic modelling, and scientists from USA were able to attend the ATT workshop. The workshop thus provided a forum for leading oceanographers from Europe and America to discuss research and technological priorities required to develop and implement a civil forecasting system for the Atlantic Ocean. The program of the workshop was organised in four sessions. Session A was devoted to the scientific background for ocean forecasting, session B to the presentation of some already existing operational experiences, session C to the definition of the goals for civilian forecasting, and session D to the presentation of some examples of actions already engaged towards these goals.

The scientific programs of the last decade, mainly TOGA and WOCE, demonstrate that significant progress has been completed in oceanography, which allows us to consider that the mean state of the upper ocean is now well known. The longer term variability (decadal) and the deeper part of the Atlantic are less well understood, but are considered as very important within the climate perspective, including major problems like the North Atlantic Oscillation. For observing and monitoring this variability, a variety of techniques are available. A basic system can be based on satellite altimetry, XBTs, and lagrangian profilers. The network does not fully exist yet at the global scale, but we are not far from it in the North Atlantic. Of course, this has to be made cost effective, and the modelling capabilities, including data assimilation, are not so far from being able to address this question.

There already exist some practical ocean dynamic forecasting experiences, at regional to basin and even global scale. They are still however in their infancy (except perhaps for the navy groups). Their experience demonstrates that we will be pushed by the data flow, and pulled by the data users. They recommend that we should take particular care of the quality control of the data and to ensure the availability of basic information on the characteristics of the instruments used for collecting the data. It is a clear that there is a need for co-operation and sharing of experience.

Numerical prognostic models and data assimilation methods are available to start forecasting experiments over the North Atlantic. And within the scientific community, there seem to be a willingness to do so. Some prototype experiments already exist. It is now time to move to real time forecasting. But to do so, there is a clear need for international co-ordination, at least for the data flows.

We can note the emergence of some initiatives for data collection in real time (see NOAA GOOS Center), for practical assimilation feasibility demonstration (see MERCATOR, GODAE and FOAM projects), and the experience of data output delivery to users.

The conclusions of the workshop thus confirm that it is timely to start forecasting experiments for the North Atlantic. An Atlantic Task Team can play an important role in helping to share the experiences, to design plans for concerted actions and to ensure the necessary co-operation for data collection.

Christian Le Provost
Chairman, EuroGOOS Atlantic Task Team

Questions to be addressed

Session A: Scientific Background for Atlantic Forecasting

- Processes and events in the Atlantic which are **now** -

  Understood and predictable with some skill on timescales of days to decades -

  - In the upper layers
  - In the deeper ocean

- Constraints on observations and modelling.

Session B: Existing operational experience

- What variables are predicted? With what skill?

  Upper ocean currents, temperatures and salinities, shelf edge processes, storms, waves, ice cover, sound velocity profiles, upper ocean heat content, etc.

- What data flow are used?

- What are the major problems encountered?

Session C: Definition of goals for civilian forecasting

- Variables to be forecast -

  - How to define them? What is needed by customers? What is feasible?

  - Should operational planning start to include consideration of deep ocean circulation?

  OR should we concentrate on the upper ocean?

- Modelling and data assimilation systems available **now** and in the **medium term.**

- Observation data required?

  - Sampling strategy, accuracy, error statistics.

- Operational requirements.

  - What can we learn from existing ocean hindcasting/forecasting experiments already developed?

Session D: Data, technology and logistics

- What data are available?

- Satellite remote sensing.

- *In situ* observations: VOS, XBTs, buoys, floats.

- What is the status of data flow handling?

- What are the new coming technologies? Tomography, AUVs.

Session A: Scientific Background for Atlantic Forecasting

What are the processes and events in the Atlantic which are now understood and predictable with some skill on timescales of days to decades in the upper and deep ocean?

- Major current paths and strengths and water mass distributions and properties are known - but not:

  - Upper ocean physical structure on diurnal to seasonal scales
  - Biological productivity as above
  - Barotropic tides
  - Internal wave climatology
  - The ocean mesoscale - climatology
  - Coastal upwelling
  - Wave climate

Less well known but of interest/importance mostly deep ocean

- Decadal scale temperature/salinity/other property changes to subthermocline depths (see Bryden paper).

- Seasonal/interannual/decadal water mass modification and spreading - including overflows (Fischer talk).

- Seasonal/interannual/decadal meridional heat/freshwater fluxes - they clearly change drastically on glacial/interglacial (and other?) timescales.

- The "coupled?" atmosphere/ocean NAO (point raised by Allan Robinson).

- Seasonal/interannual patterns and changes in primary productivity and fish stocks (cod and climate - publications by Dickson).

- Boundary processes between shelf and deep ocean (Stephens talk) and role of the slope as a boundary condition for the shelf seas.

What are the likely observational methods to be used in observing the Atlantic?

- Continuation of highest quality altimetry, SST, scatterometer winds, ocean colour from earth observing satellites. (What spatial temporal coverage is needed? i.e. How many satellites?).

- Repeats (every 10 years? How often should they be?) or already-repeated sections. (Highest quality, full depth, including tracer including CO2 inventories).

- Maintenance of existing time series stations.

- Establishment of new sites in key areas (based on alternative technologies - profiling CTDs?).

- Establishment and maintenance of a P-ALACE based, basin-wide monitoring of upper ocean (top 2000m) T and S (and other properties?). Needs confirmation of long-term sensor performance and design of a seeding strategy.

- Maintain XBT lines at least until P-ALACE is established as a viable alternative.

- Monitoring of transports of major currents. (Gulf Stream by altimetry and *in situ* measurements). Deep overflows by moored arrays.

- *In situ* sea level measurements.

- Acoustic tomography/(Thermometry?) for convection monitoring (and basin scale temperature changes?).

- Drifter measurements of surface currents, SST, atmospheric P, surface salinity.

- Surface salinity from VOS.

- Ship mounted ADCP (of limited value for currents outside major systems) monitor biomass. Upward looking of more value.

- Ice monitoring (upward sonar and satellite).

What are the requirements to make progress in modelling?

- Computing resources (people, CPU, storage).

- Explore the extent to which the physical/ biological parameters are predictable.

- Verification of existing (new models by model/model and model/data inter-comparisons.

- How do we initialise coupled models?

- Production and acceptance of validated "actual" forcing fields.

- Improved understanding and then parameterisation of important ocean processes (e.g. mixing).

- Use of new improved bathymetry and bathymetric statistics (derived from altimetry?).

- Can long runs of coupled models produce the interior decadal scale changes seen in the ocean?

- Continued development of 4-D data assimilation to produce time varying state of the ocean.

Session B: Existing Operational Experience

Presentation of products to users

Present experience suggests two data streams - observation, and model products. Data supply can be 'push' or 'pull'. Some applications (e.g. Numerical Weather Prediction (NWP), real time ocean forecasting) are best served by 'push' of data to them, by data suppliers.

Other applications e.g. dissemination of model products or value-added observation may be well served by website supply/dial-up fax and 'pull' of data by data users.

There is a strong requirement for the supplier to seek feedback about adequacy of the data supplied. Metadata (e.g. instrument type and characteristics/model formulation) are also required.

For ease of maintenance, many centres make use of modular models - a unified model can cover global, regional and mesoscale areas with much of the code common to all applications. There may be need for configuration control, and information on changes to a model should be available to users.

There is a well-established process of observation monitoring in NWP and this can serve as a foundation for oceanographic observation monitoring. This is important for the oceans as synoptic scales are smaller and in-situ data volumes are smaller than for the atmosphere. Information about observation type (instrument/characteristics) should be available and a start has been made on oceanographic OSS (simulation) in order to help define a cost-effective observation network. This should be encouraged and supported.

The error characteristics of new instruments need to be established to avoid introducing spurious "climate" signals into long-term time series.

There is a need for dialogue with developers of NWP models to ensure that the needs of ocean models, in terms of surface fluxes, are considered.

Application of high resolution ocean models requires consistency of, for example, SSTs, with the NWP model supplying the fluxes. Ideally, a coupled ocean-atmosphere run should be performed.

Present experience with *in situ* observations highlights the need for international co-ordination, and consistency checks.

Session C: Definition of goals for civilian forecasting

Objectives

- Establish a best possible operational system as quickly as possible based on existing components and technology.
    - This demonstrates capability, need for data and the usefulness of products.
- Establish a forum for international co-operation and interaction.
    - This is important for co-ordinating real-time data flow and validation of results.
- Define a strategy for operational in-situ data collection.
- Focus on a best possible basic system for the general circulation and ecosystem.
    - Deep ocean circulation is important even if we only focus on surface processes.
    - Start by focusing on short timescale forecasts. (Still work to do before we start decadal predictions).
- What about an "ECMWF" type centre for running the operational systems?

Session D: Data, technology and logistics

Summary of presentations

Results from a EuroGOOS customer survey indicate that there appears to be as much interest in the large scale deep ocean as the smaller scale shelf seas. There is consistency in the priorities for oceanographic variables and applications between those in different European nations whose views have been sought.

The French Mercator project is a broadly based, long-term, significant investment which should create a global capability in operational oceanography for the early part of the next century. It is built upon very substantial past investments in France, and elsewhere, in observing systems and modelling and data assimilation methods and is designed to meet the needs of a wide range of end users including the scientific community. Its planned development stages include a low resolution global capability and a high resolution system covering the whole of the Atlantic. It is intended to take advantage of the WOCE observational phase and will clearly be an important part of GODAE.

NOAA is making and will continue to make a substantial contribution to the *in situ* observational network and is committed to monitoring the quality and utility of the data and the data transmission and collection systems. The latter will be an important aspect of the work of the NOAA GOOS centre.

There is a need for a dedicated effort for generation of products from model and observed data which are tailored to the needs and interests of end users. It is essential to exploit the new commodity technology, like the internet and PC based systems, as a means of dissemination and collection of data.

General conclusions

A substantial and comprehensive suite of satellite data is and will remain in place. There is a rich range of technologies available for *in situ* observations, and there are groups which co-ordinate effort on single *in situ* data types, but there is no forum which co-ordinates the design and implementation of the *in situ* observational system as a whole. Acoustic thermometry has potential for monitoring of climate change on the large scale. Moored and yo-yoing CTDs, AUVs, gliders and cycling RAFOS are also promising emerging technologies. The fouling of conductivity instruments needs to be addressed. Satellite altimeters have an important role to play in the determination of bathymetry.

The GTS system for real-time transmission, and other methods for delayed-mode transmission, work tolerably well, but there is a need to study the use of alternative technologies particularly those based on the internet. Sufficient access to modern extremely powerful computers is necessary for the modelling and assimilation efforts.

We believe that there should be a policy of free, open and timely exchange of oceanographic data to mirror that in meteorology. We suggest that observing systems should be designed so that it is feasible to produce timely quality controlled data.

To extract the maximum return from joint investments, a forum is required to resolve practical logistic issues in the design and responsibilities for maintaining observational systems.

Session A: Scientific background for Atlantic forecasting

What we can learn from WOCE about the constraints on future observations and modelling in the Atlantic

John Gould
Southampton Oceanography Centre, UK

Introduction

The World Ocean Circulation Experiment (WOCE) is a component of the World Climate Research Programme. Following the short but successful SeaSat satellite mission in 1978, WOCE was designed during the 1980s to take advantage of planned earth observing satellites scheduled for the early 1990s. These satellites could, for the first time give a truly global and quasi-synoptic perspective on ocean observations.

WOCE has been the biggest oceanographic experiment ever undertaken. Its aim, in short, is to develop better ocean models for use in climate prediction research and to collect the data required to test these models. The observational phase of WOCE ended at the end of 1997 but WOCE will continue in a phase of Analysis, Interpretation, Modelling and Synthesis (WOCE AIMS) until the end of 2002. (WOCE IPO, 1997a,b)

Despite WOCE being a climate-related programme there are lessons to be learned that are applicable to the design of ocean observing systems for a much wider range of applications and specifically lessons from experience in the North Atlantic that might be of use to EuroGOOS.

WOCE in the North Atlantic

The North Atlantic has been, and no doubt will remain, the best observed of all the ocean basins. The reasons for this are partly logistical - the N Atlantic is bordered by most of the nations that are well equipped to make ocean observations. The second reason is that in a global context, the N Atlantic is important, it (and its marginal areas) are the source of much of the marine food used in the developed world and a significant part of the world's hydrocarbon resources. It is also a critical component in the earth's climate system.

For this latter reason the N Atlantic was the focus of much effort in WOCE

a) to enable the variability already known from historical data to be better understood and
b) to use the N Atlantic as a test bed for a number of so called "Process Experiments"

The most ambitious plans for the North Atlantic observations during WOCE were not fully realised; however it remained the subject of intensive study particularly in 1996-7.

Within the North Atlantic, WOCE will have occupied some 8500 full depth hydrographic stations between 1990 and 1997 and used some 4000 days of ship time (for hydrographic and other cruises). However, in terms of temporal and spatial coverage of ocean properties this represents only 1 full depth hydrographic station per 100km x 100km square every 4 years! - very sparse coverage for such a major effort. (WOCE IPO 1997a)

The hydrographic stations have, for the most part, been collected at closely spaced (typically 50km or less) intervals along widely separated lines. This strange, but logistically sensible, station distribution makes mapping of properties, or data assimilation into models, a difficult task.

Temporal variability

The longest time series of physical properties in the ocean interior are from a very few stations and repeated sections. e.g. Osterhus, Gammelsrod and Hogstad (1996), Joyce and Robbins (1996).

These reveal changes in temperature and salinity that have large space and time scales and are not confined to the upper ocean.

However, mean property fields can be determined and temporal changes from previously-occupied sections have been determined. (Parrilla *et al.,* 1994). These changes have proved to be of greater magnitude and spatial extent than previously expected.

WOCE has also collected XBT data (mostly from the upper 750 m) at a rate of around 6000 profiles per year. Again these have been largely restricted to major shipping routes and hence do not give ideal spatial coverage. However they enable seasonal changes in upper ocean thermal structure to be documented and can be used to initialise and verify predictive models such as FOAM.

Central to WOCE has been the TOPEX-POSEIDON altimeter satellite giving spatial and temporal information on sea surface slopes.

Model validation

The validation of models is a complex process but is central to WOCE objectives. Each model has a different formulation and physical configuration, different boundary conditions, and in general there are as yet no standard, forcing fields that are accepted as a single benchmark and such fields as are available have defects. We are still learning, in projects such as the EC-funded Dynamo (The Dynamo Group 1997), the strengths and weaknesses of each model in representing various ocean fields. The comparisons of the WOCE data sets with a wide range of models will be a major international undertaking for the next 5-10 years. (WOCE IPO, 1997b).

While the open ocean areas of the North Atlantic will be of direct relevance to some parts of EuroGOOS, models of these areas will provide boundary conditions to the European shelf and marginal seas and the physical models from WOCE will provide an underpinning to chemical, biological and ecosystem models.

Development of new observing systems

Cost-effective data collection systems will be needed to satisfy the requirements of future operational (GOOS/GCOS), pre-operational (GODAE) and research (CLIVAR) programmes. WOCE has, with varying degrees of success, stimulated the development of some of these systems. A notable success has been the profiling ALACE (P-ALACE) float. Deployed in large numbers in the North Atlantic in 1996-7, (Fig 1) each float is capable of providing of order 200 CTD profiles to subthermocline depths at a cost of order $100 per profile. Long-term stability of the profiler sensors is still being evaluated but there is evidence that in the best cases sensors are capable of ±0.005 in salinity over a year. Solution of the long term salinity problem is a major task for the profiling floats and for moored profiling instruments that have been deployed but that are yet to provide long term records of the type that might enhance the, now sparse, network of ocean time-series stations.

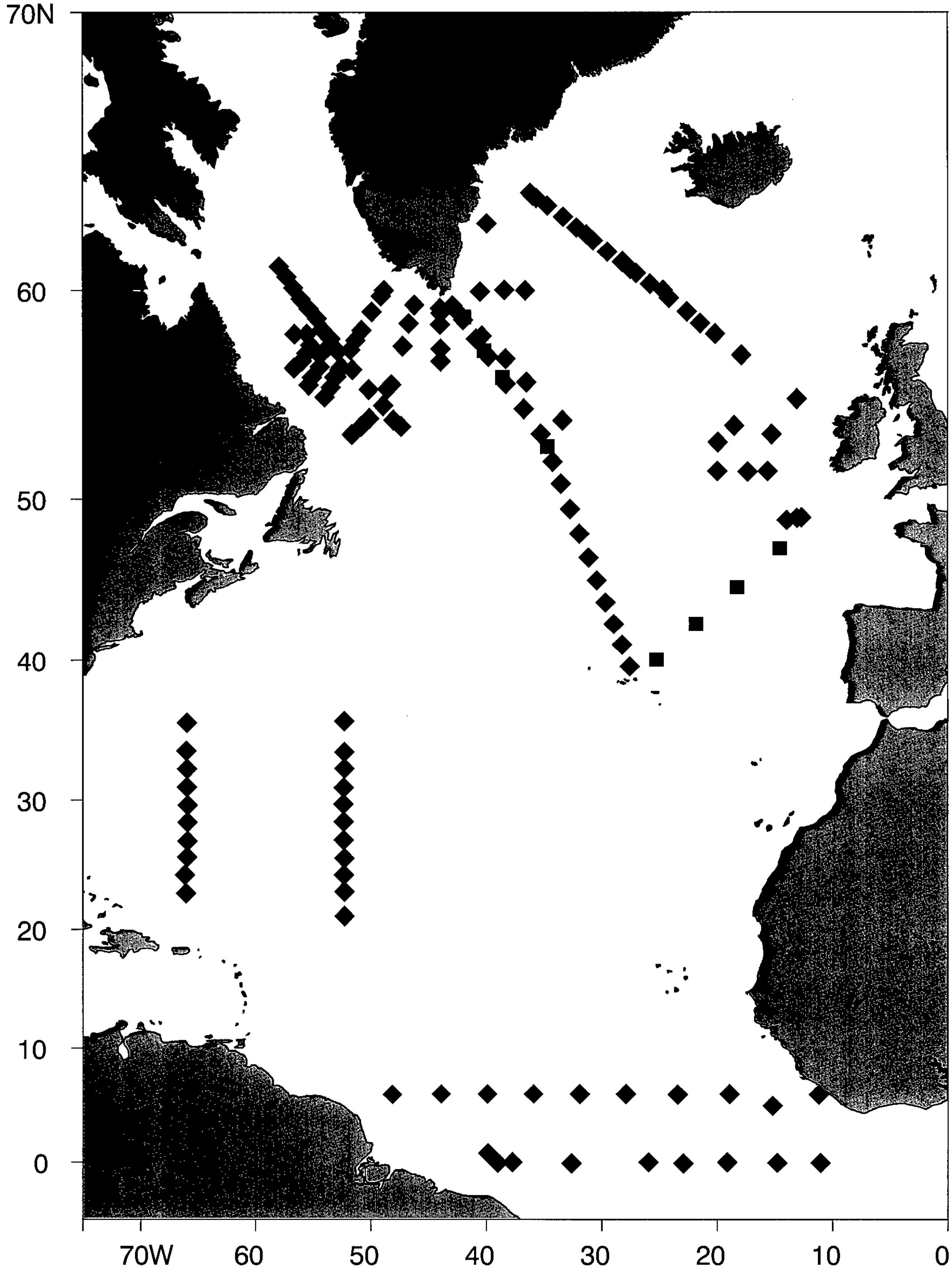
Enhancements of existing observational systems such as satellite-tracked drifters (lifetimes have been doubled and windage almost eliminated), improved ADCP data from state-of-the-art GPS navigation (by differential GPS for position to about 3m accuracy and 3-D GPS for heading information to 0.1 degree) and the use of data capsules to reduce offshore tide gauge data recovery costs have all been made during WOCE. A EuroGOOS North Atlantic programme needs to embrace these technology developments and to build on them in key areas.

Summary

Models will ultimately be the means by which we will portray the state of the ocean. Therefore EuroGOOS needs to keep in close touch with the Analysis, Interpretation, Modelling and Synthesis (AIMS) phase of WOCE and to embrace its model-model and model-data intercomparisons and the development of ocean data assimilation techniques that will be central to it.

WOCE observations per se will soon end but through CLIVAR and perhaps later in GODAE ocean observation systems will develop based on WOCE experience and these will be of direct interest to EuroGOOS.

Deployment sites for WOCE Profiling ALACE floats in 1996-97



(Courtesy of B. Owens, WHOI)

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Dependence of Gulf Stream Simulations on Grid Resolution, 1/4º to 1/32º

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Hydrodynamic versions of the NRL Layered Ocean Model (NLOM) have been used to simulate the Atlantic subtropical gyre (9°N-47°N) including the Caribbean and Gulf of Mexico. Grid resolutions range from 1/2° to 1/32° for each variable and up to 5 Lagrangian layers in the vertical. The model has a free surface and allows diapycnal mixing, isopycnal outcropping, and inflow/outflow through the ports at the model boundaries to simulate the thermohaline component. The model runs efficiently and interchangeably on all DoD High Performance Computing platforms configured for applications this large, including massively parallel distributed memory computers and multi-processor shared memory computers (Wallcraft and Moore, 1996).

Numerous simulations have been run at 1/2° to 1/32° grid resolution to investigate model sensitivity to different atmospheric forcing sets (Hellerman-Rosenstein (1983) and COADS), the bottom topography, model configurations and parameters, initial states, and the northern and southern boundary conditions. In general, the simulations were spun up to statistical equilibrium at coarser resolution, then continued progressively to new statistical equilibria at finer resolution. Snapshots of sea surface height from the 1/4° and 1/8° simulations forced with the Hellerman-Rosenstein monthly wind stress climatology and a 14 Sv thermohaline component (Fig. la,b) show 2 Gulf Streams, one flowing east of Cape Hatteras and one to the north that follows the model boundary. The dual pathways are similar to those found in the linear solution. Realistic Gulf Stream separation at Cape Hatteras occurs in the 1/16° simulation (Fig. 1c), but realistic separation and a realistic pathway for the Gulf Stream between Cape Hatteras and the Grand Banks is only seen at 1/32° resolution (Fig. 1d).

0(1) changes from linear solutions are required to simulate a realistic Gulf Stream pathway between Cape Hatteras and the Grand Banks. This was robustly achieved only at 1/16° and 1/32° resolution, but more so at 1/32° with or without a deep western boundary current (more accurately with). These results have been compared with various observational results, including those from the Data Assimilation and Model Evaluation Experiments - North Atlantic Basin (DAMEE-NAB) project. Ibis includes a comparison between a 6-year model mean over years 6-11 at 1/32° resolution and a 15-year mean Gulf Stream IR northwall pathway over 1982-1996 (Fig. 2a). Some noteworthy changes are found at 1/32° vs. 1/16° resolution. These include much greater eastward penetration of high Gulf Stream eddy kinetic energy and an eastward extension of a strong non-linear recirculation gyre on the south side of the Gulf Stream. As shown in Fig. 2b there is a local maximum in sea surface height near the eastward extension of a strong non-linear recirculation gyre on the south side of the Gulf Stream. As shown in Fig. 2b there is a local maximum in sea surface height near the eastern terminus of this gyre located within one degree of the one seen in the U.S. Navy's GDEM climatology (Teague *et al.*, 1990). Associated with this is an eastward extension of the high abyssal eddy kinetic energy consistent with an observed maximum at 55°W (Schmitz, 1984). Two mean pathways are shown feeding into the North Atlantic Current near the Grand Banks, one along the southern slope of the banks and one from about 40°N, consistent with observations (Dietrich *et al.*, 1980; Schmitz, 1996; Carr *et al.*, 1995). The 1/32° model also shows small temporal variation in Gulf Stream latitude for a few degrees east of Cape Hatteras, consistent with 4 years of repeated ADCP sections at 70°W by Rossby *et al.*, (1996), and less variation than seen in the 1/16° model. It also shows close agreement in latitude with the Rossby *et al.*, (1996) observations. In the past, realistic Gulf Stream separation has been achieved only 1) as a transient or 2) with realistic separation at Cape Hatteras but a grossly unrealistic pathway in the interior of the basin or by using 3) unusual atmospheric forcing, 4) a limited area model, 5) a partially diagnostic model, or 6) unobserved inflows from the north above the abyssal layer.

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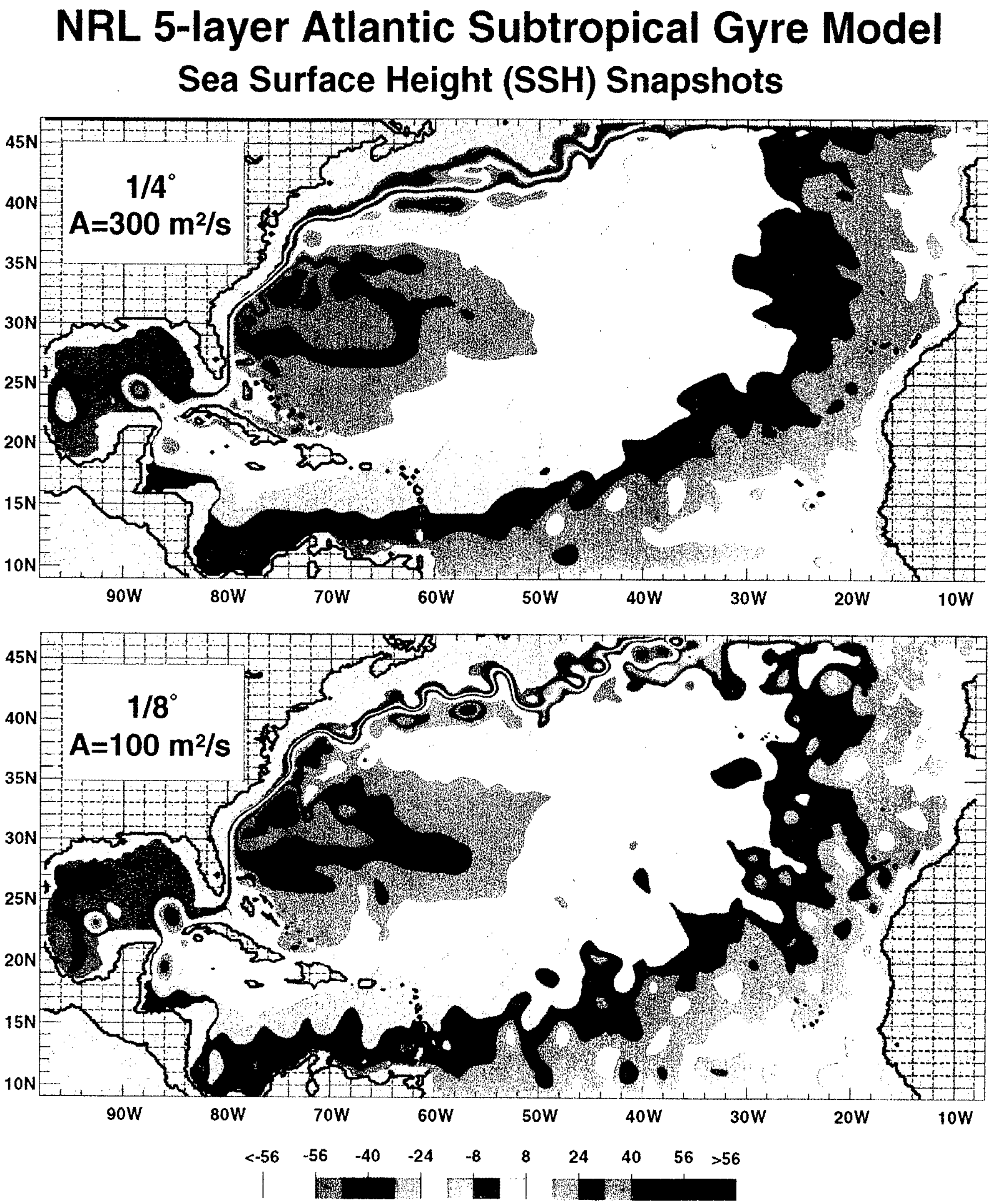

Figure 1(a,b). January snapshots of sea surface height from (a) a 1/4° degree model and (b) a 1/8° model. Both models were forced by the Hellerman-Rosenstein monthly wind stress climatology and ports at the northern and southern boundaries (the thermohaline component).

NRL 5-layer Atlantic Subtropical Gyre Model

Sea Surface Height (SSH) Snapshots

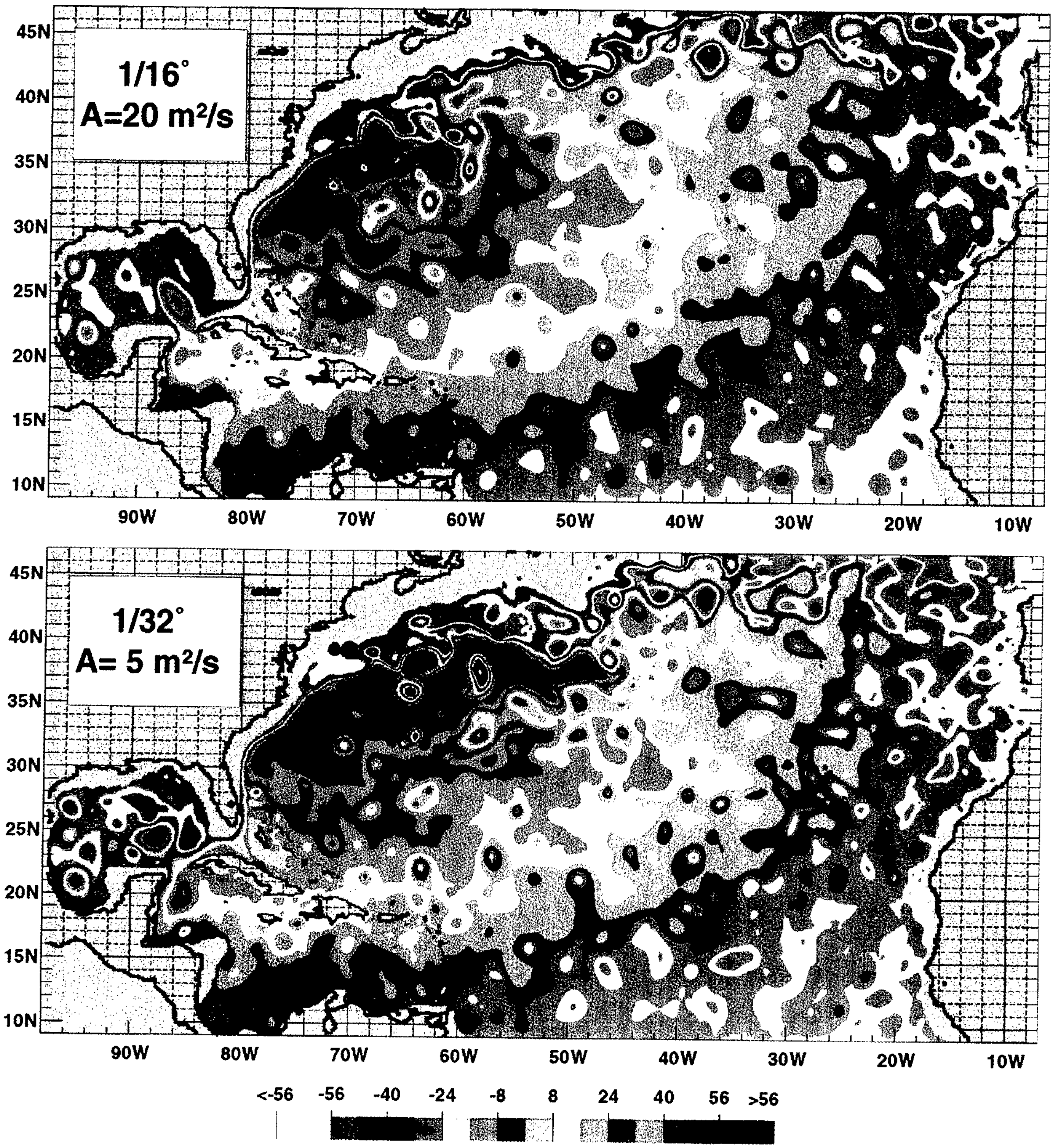

Figure 1(c,d). January snapshots of sea surface height from (c) a 1/16° degree model and (d) a 1/32° model. Both models were forced by the Hellerman-Rosenstein monthly wind stress climatology and ports at the northern and southern boundaries (the thermohaline component).

Gulf Stream Pathway Comparison
NRL 1/32° Atlantic Subtropical Gyre Model

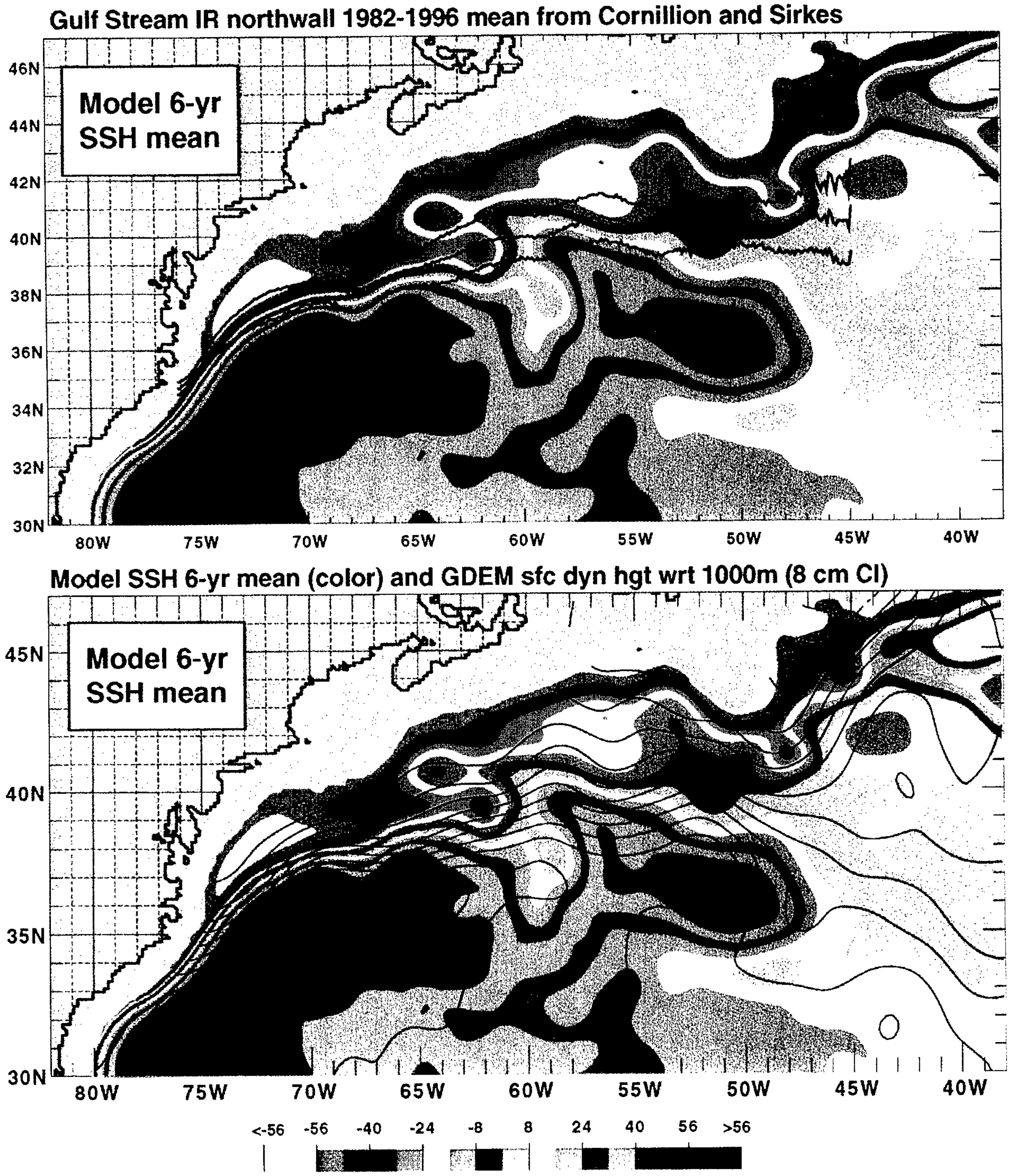

Figure 2(a,b). Model mean sea surface height formed from 6 years of model data (in color) and (a) mean northwall determined from 15 years of IR data and (b) surface dynamic height relative to 1000 m from the U.S. Navy's GDEM climatology.

The Ability of High-Resolution Ocean General Circulation Models to Represent the North Atlantic Ocean

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Southampton Oceanography Centre, UK
and the DYNAMO Group

There are at present three distinct classes of Ocean General Circulation Model available for simulating the world's oceans. These differ in their representation of the vertical co-ordinate, and use either fixed levels, layers of constant density, or terrain-following co-ordinates. One effective way of learning about the capabilities of these ocean models is to compare them both with each other, and with observations. Here we describe results of a model intercomparison exercise called DYNAMO (Dynamics of North Atlantic Models: Simulation and assimilation with high resolution models), which was funded by the EU through the MAST-II programme (contract number MAS2-CT93-0060). The project involved a "level" model run by Kiel University in Germany (based upon the GFDL model), an "isopycnic" model from SOC (based on the Miami Isopycnic Co-ordinate Ocean Model, MICOM), and a "sigma" model (with "terrain-following co-ordinates") implemented by Grenoble University in France (based upon the SPEM model). The models were all of the same high horizontal resolution (1/3° longitude, sufficient to permit ocean eddies), covered the North Atlantic from 20°S to 70°N, and were all forced in the same way, using identical and realistic data sets derived from the ECMWF analysis, to represent the winds, and heat and freshwater fluxes at the ocean surface.

A principal result of the project is that all three models were successful in simulating the North Atlantic with a considerable degree of realism, and many important insights have been gained into the way in which the ocean works. Further, aspects in which the models provide different solutions, or differ from the observations, provide direct guidance as to what improvements are most crucially needed to develop the next generation of models. Although the work is still in progress, the most important preliminary results are summarised below:

There are significant differences in the pathway of the North Atlantic Current between the three models, which give strikingly different patterns of sea-surface temperature, and surface density, and depth of wintertime convection at high latitudes. These differences are under investigation, but strong topographic control is apparent in the sigma model. Clearly, the pathway of the North Atlantic Current is a key feature which basin-scale forecasting-assimilating models need to predict correctly.

The production of North Atlantic Deep Water, an essential part of the global circulation, is in the models principally affected by over-active physical mixing as deep outflows transit southwards through narrow channels across the Greenland-Scotland ridge in the level and sigma models, and by utilising in the isopycnic model a density co-ordinate (referenced to the sea surface) which does not adequately describe the contrasts between deep water masses. However, improvements are now in progress (in the wider modelling community) to improve these aspects of the models.

The Azores Current (a major feature in the central Atlantic), which "occurs" only in the isopycnic model, provides a controlling influence in determining the ventilation of the subtropical gyre, and hence the circulation and dynamics of the upper ocean water masses over much of the mid-latitude regions. This is therefore another feature which forecasting-assimilating models need to predict correctly.

The net Northward heat transport in the "level" model is low, compared with deductions from observations, and compared with the other models, possibly because of horizontal mixing through sloping density surfaces on the western side of the ocean. Again, new specifications for the mixing in ocean models, replacing the horizontal mixing by mixing along density surfaces, have recently been developed, and can now be implemented in high-resolution ocean models.

The eddy field is weak in the isopycnic model, compared with the other models, possibly because of the way that the mixing of momentum is included (via harmonic friction as

opposed to biharmonic, and with a formulation which provides high viscosities in regions of horizontal shear). Again, this insight should now lead to model improvements.

All the models describe the flows around the European margins surpassingly well, and give insights into the processes occurring. They all reveal upwelling off Portugal and Northern Spain in the summer, and poleward surface flows bringing warm, saline waters northward in the winter. In addition, they show that salty Mediterranean Water moves northwards, but only as far as the southern Rockall Trough. High salinity water travels northwards (in the isopycnic model at least) in the surface flow around the European margins from the Iberian shelf to the Iceland-Scotland area. There it is subducted onto density surfaces corresponding to the Mediterranean Water, so explaining the presence of salty water that far North. It may also be drawn into the North Sea.

Our conclusions are then:

1. Model intercomparisons such as DYNAMO are giving many insights into the ocean circulation, and into the current capabilities of the models for representing the important flows and processes. This is leading to continuing improvements in all the model types, which will in turn lead to better forecasting/ assimilating models.

2. Assessing the seasonal variability of basin-wide models could provide valuable inputs into designing monitoring and observing strategies, for collecting data sets to assimilate into forecasting models. For instance, valuable and limited resources (in the form of survey ships etc.) could be concentrated on those areas of the ocean which are most variable, while those areas which do not show strong seasonal cycles could be surveyed less often.

3. Basin-scale models (such as those in DYNAMO) are now able to provide good descriptions of the flows around the European margins, which may often extend over considerable distances, and also can describe the impacts of currents in the deeper ocean upon the shelf-break environment. It seems, therefore, that very high resolution, but limited area models of the European shelves and slopes will benefit from being coupled to basin-wide models: these models may well be able to provide more realistic boundary conditions at the edges of the shelf models than can be derived from seasonal hydrographic climatologies, which cannot properly describe the relatively fine-scale currents involved. This will lead to improved forecasts for shelf and shallow seas.

The results of the DYNAMO project are described fully in the final scientific report by the "DYNAMO Group" (Barnard *et al.*, 1997), a limited number of copies of which can be obtained from the author of this report. The wintertime surface temperature patterns for all three models are shown in the attached figures.

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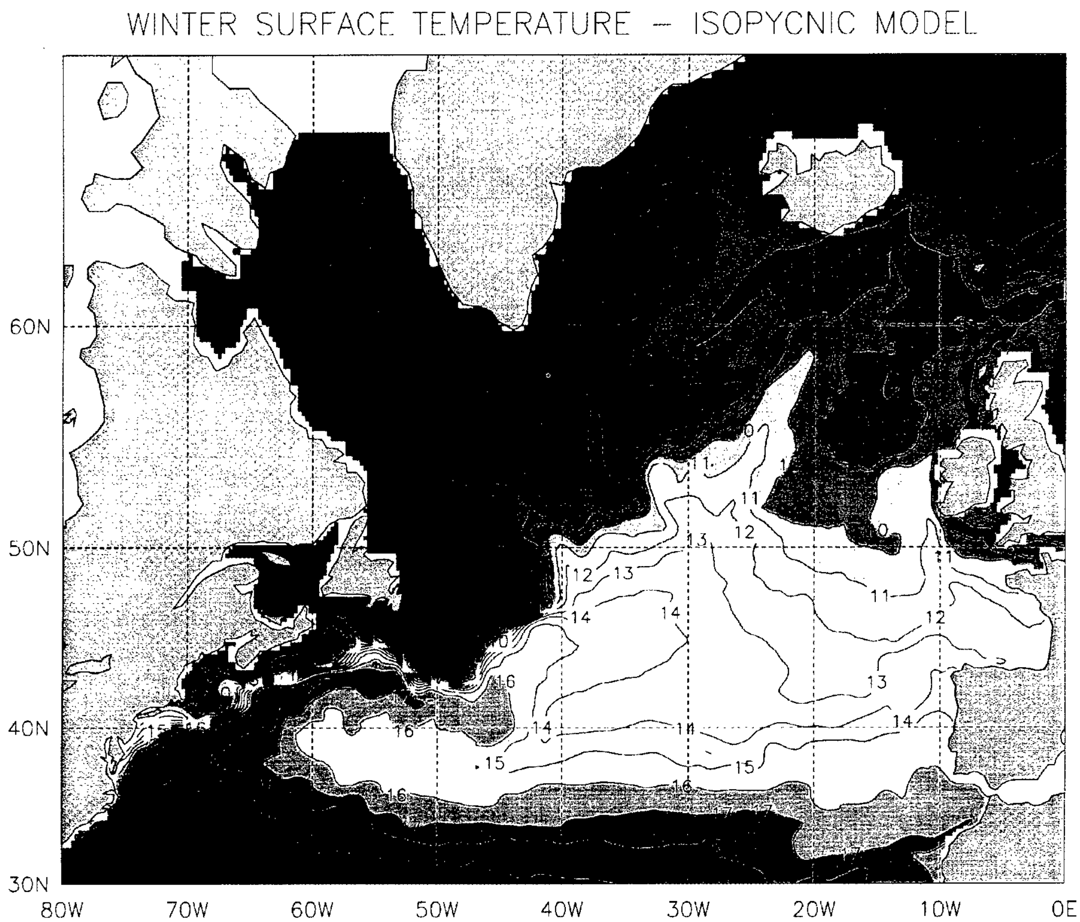
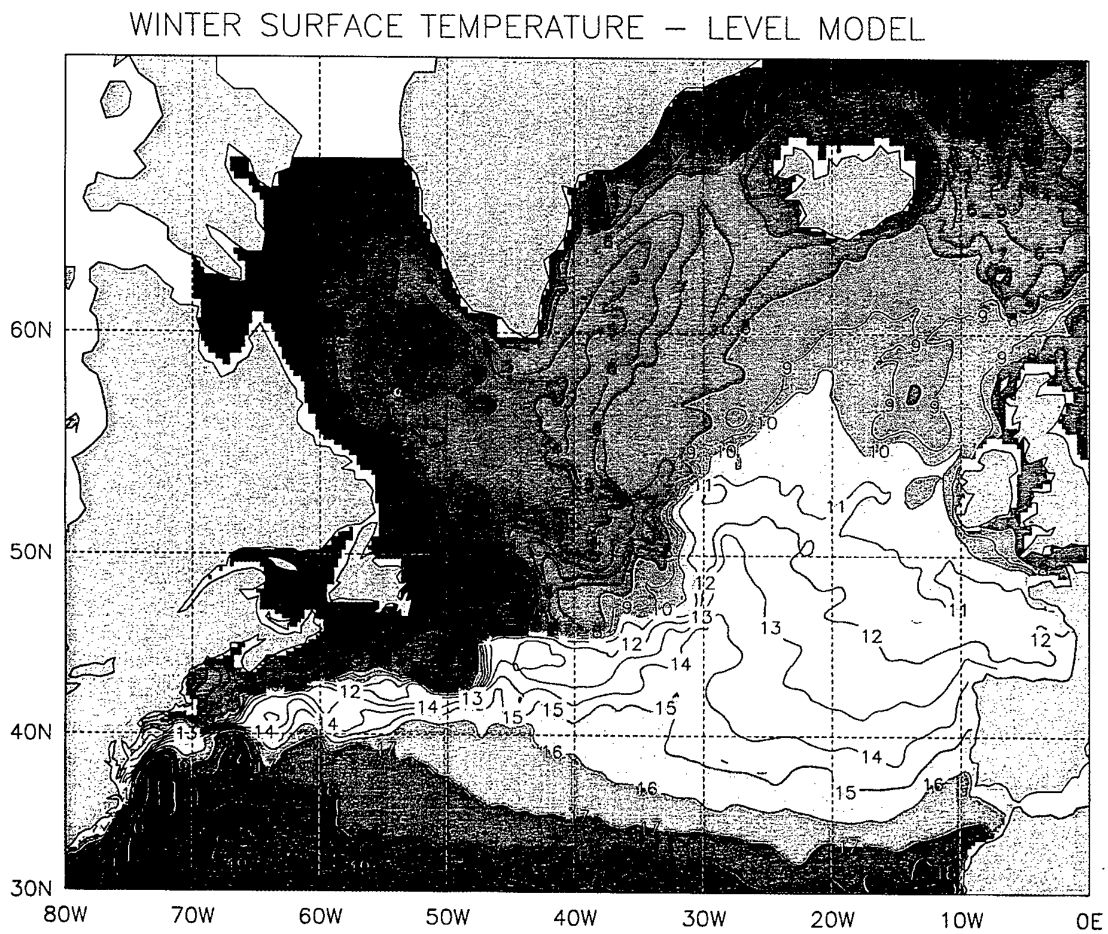
Figure 1



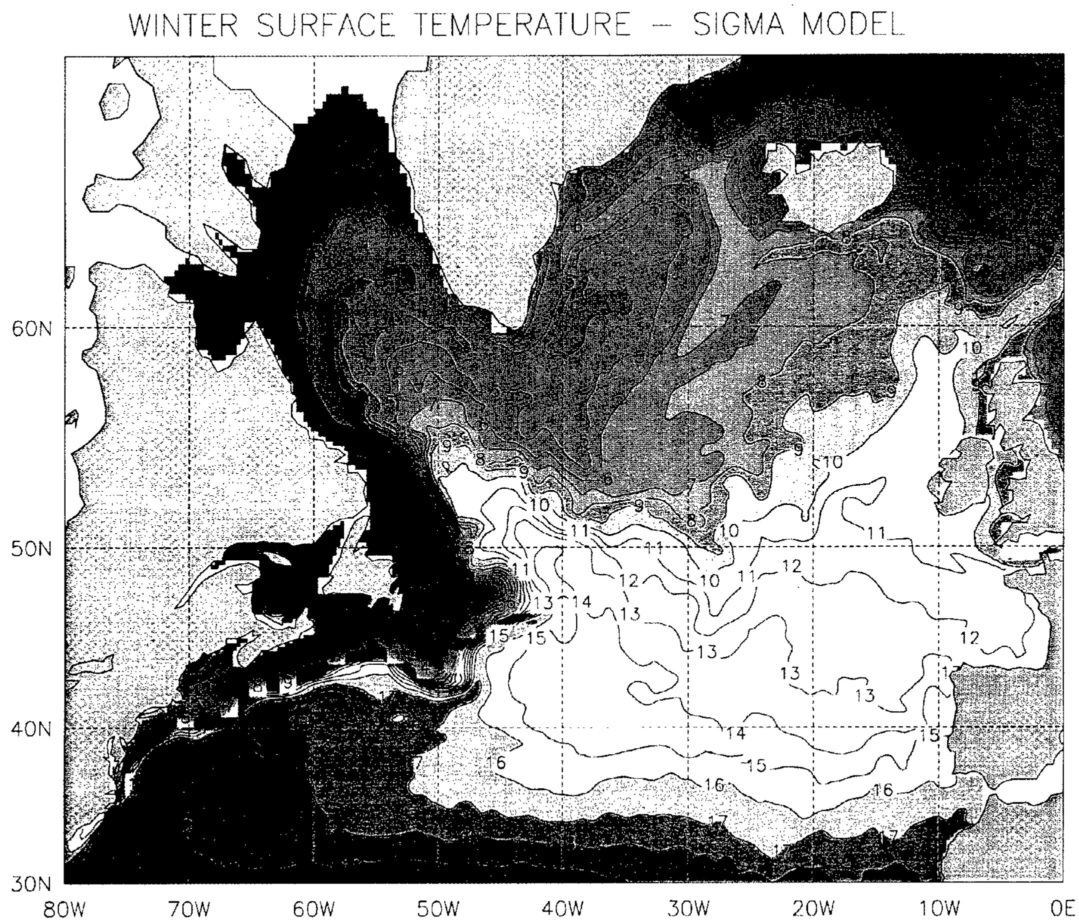
WINTER SURFACE TEMPERATURE – ISOPYCNIC MODEL
60N
50N
40N
30N
80W
70W
60W
50W
40W
30W
20W
10W
0E

Figure 2



WINTER SURFACE TEMPERATURE – LEVEL MODEL
60N
50N
40N
30N
80W
70W
60W
50W
40W
30W
20W
10W
0E

Figure 3



WINTER SURFACE TEMPERATURE – SIGMA MODEL
60N
50N
40N
30N
80W
70W
60W
50W
40W
30W
20W
10W
0E

Decadal predictability in the North Atlantic?

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Abstract

We discuss recent evidence suggesting that decadal fluctuations in North Atlantic SST may be predictable. The predictability arises from propagation of SST anomalies and a quasi-decadal periodicity. The propagation is likely to be advective, but the propagation speed is much slower than the near surface currents. The periodicity can be identified in a dipole-like pattern of atmospheric variability as well as in SST. This correlation may indicate an oceanic influence on the atmosphere, but more work is required to establish whether any such an influence is strong enough to be important. We conclude by listing a number of outstanding issues that need to be addressed before we can better assess the prospects for decadal forecasting of climate.

Introduction

If the comparative predictability of the oceans is to be exploited to forecast natural fluctuations in climate, a necessary (but not sufficient) condition is an ability to forecast Sea Surface Temperature (SST). Much of the variability in North Atlantic SST can be explained as a local oceanic response to atmospheric variability. To the extent that this is the only important mechanism, predictability of SST is unlikely to exceed the typical decorrelation time of anomalies in the mixed layer, i.e. a few months. Non-local processes in the ocean (advection, Rossby wave propagation), however, may be source of predictability on longer timescales. In the extratropical oceans away from boundaries such processes are typically characterised by decadal timescales. We are therefore prompted to enquire whether the observed characteristics of decadal fluctuations in SST give any indication of predictability.

Observed features of decadal fluctuations in North Atlantic SST

An examination of decadal variability in North Atlantic SST over the last century suggests the presence of two principal timescales. The first, discussed for example by Kushnir [1], is a roughly century timescale fluctuation characterised by relatively cool temperatures at the beginning of the century, warm temperatures in the 1950's and 1960's, and more recently some cooling. The second is a more nearly decadal timescale. Deser and Blackmon ([2], hereafter DB93) identified a fluctuation with a period around 12 years (post WWII). The associated spatial pattern has largest weights east of Newfoundland with smaller weights of opposite sign off the SE coast of the U.S.A. DB93 suggested that the relationship between the atmospheric and oceanic fluctuations was consistent with SST anomalies arising as a local mixed layer response to atmospheric fluctuations. However the more recent analysis of Sutton and Allen ([3]; hereafter SA97) showed that the situation is more complicated.

Fig. 1 (from SA97) shows the correlation between low frequency fluctuations in local wintertime SST and low frequency fluctuations in wintertime SST averaged over the region 80-60° W, 31.5-38.5° N (the vicinity of Cape Hatteras, hereafter VCH) as a function of lag in years. SST fluctuations appear to propagate from the coast of North America across the Atlantic to the north west of Scotland following the strong SST gradients that are associated with the Gulf Stream and North Atlantic Current (NAC).

An examination of the SST anomalies that give rise to the correlations shown in Fig.1 reveals propagating features (also identified by Hansen and Bezdek [4]) arising on the same quasi-decadal timescale that was identified by DB93. The propagation speed, at ~1.7 cm/s, is surprisingly slow. If, as seems likely, these signals are advective their speed must presumably be determined by the weaker currents either to

one side of the Gulf Stream core or at some depth below the surface. Subsurface observations close to the path of the Gulf Stream / NAC show evidence of decadal temperature fluctuations, possibly extending below the seasonal thermocline [5, 6, 7].

The relationship between decadal fluctuations in the atmosphere and decadal fluctuations in the ocean

The quasi-decadal fluctuations in SST are correlated with fluctuations in a dipole-like pattern of variability in North Atlantic Sea Level Pressure ([2, 3]). These atmospheric fluctuations certainly influence the ocean locally, as suggested by DB93. It seems unlikely, however, that local atmospheric influence alone can explain the propagation of SST anomalies discussed above. More likely is a scenario in which the propagation arises in the ocean and both the propagation and the local atmospheric influence combine to determine the decadal fluctuations in SST. Interference between these influences offers one possible explanation for the emergence of a preferred timescale [8, 3].

Although identification of the quasi-decadal timescale in the atmosphere is suggestive, it is still unclear whether a significant influence of the ocean on the atmosphere is required to explain the observed decadal variability in North Atlantic SST. The influence of extra-tropical SST anomalies on the atmosphere remains poorly understood. SA97 suggested that the atmosphere might be particularly sensitive to SST fluctuations in a key region of cyclogenesis off the SE coast of the U.S.A. This hypothesis is now being tested, but results are not yet available. However, a recent analysis of an ensemble of atmospheric model integrations [9] suggests that, given a knowledge of SST, atmospheric fluctuations are most predictable in the subtropical Atlantic, while at higher latitudes internal variability is likely to swamp any atmospheric signal induced by SSTs.

Conclusions and Outstanding Questions

We have discussed some encouraging evidence that certain decadal fluctuations in North Atlantic SST may be predictable. The predictability arises from propagation of SST anomalies and a quasi-decadal periodicity. This periodicity can also be identified in the atmosphere. We are not yet able to give a full account of the mechanisms responsible for these decadal fluctuations. Issues that need to be examined more closely include:

1. How do mixed layer processes interact with non-local processes in the ocean (advection, Rossby wave propagation) to determine decadal fluctuations in SST? What determines the speed of propagating anomalies?

2. What is the relationship between the two decadal timescales that can be identified in North Atlantic SST? Can they be associated with variability in the wind driven and thermohaline circulations?

3. What is the influence on the atmosphere of decadal fluctuations in extratropical SST?

4. What is the role of remote processes, for example in the Pacific, on decadal fluctuations in the North Atlantic region?

5. What is the actual predictability of decadal fluctuations in SST, and is there any useful decadal predictability for the atmosphere?

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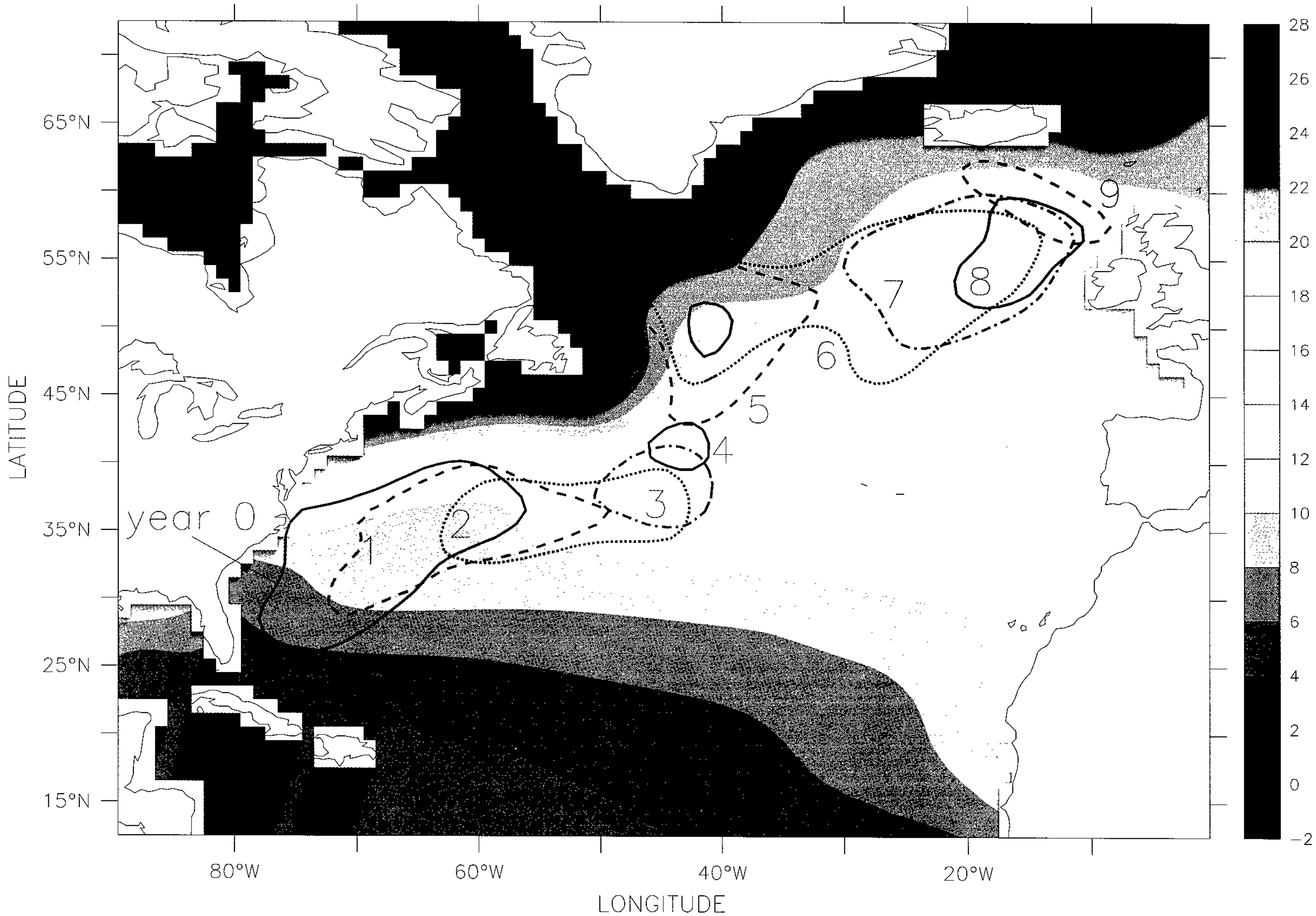

Correlation between low frequency fluctuations in local wintertime SST and low frequency fluctuations in wintertime SST averaged over the region 80-60° W, 31.5-38.5° N (the vicinity of Cape Hatteras, VCH) as a function of lag. The contours pick out the regions where lag-correlation with VCH is maximised. The numbers next to each contour indicate the lag in years. In all cases VCH SST leads local SST. The contour value is 0.8 for lags of 0 to 8 years and 0.75 for the lag of 9 years. The contours are superimposed on the SST field averaged over all winters between 1945 and 1989 (colour scale in ° C). After Sutton and Allen (1997, [3]).

Monthly mean SST data were obtained from the NOAA SMD94 analysis of ship observations for the period 1945-1989 on a 1° x 1° grid. The long term mean annual cycle was removed from all the data. Winter-mean anomalies for each year are then computed by averaging the SST anomalies for the months November-April, and a five-year running mean is applied to the winter-mean anomalies. Correlations are only computed in the latitude band 25-65° N.

Monitoring, modelling and prediction of multi-annual and decadal changes (Abstract)

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Oceanographers have long considered the deep ocean to be reasonably constant in time so that observations over many years could be combined into a single description of the mean ocean circulation. Indeed, a primary objective of the World Ocean Circulation Experiment (WOCE) is to provide a fundamental description of the global ocean circulation. Comparison of new WOCE measurements with historical data, however, is revealing remarkably large changes in the thermocline and deep ocean and these changes involve vertical movements of constant water mass structures as well as changes in the potential temperature / salinity relationships which define the water masses. The clearest signal is in the subtropical North Atlantic Ocean where intermediate and upper deep waters are warming at a rate as large as 1°C per century and there is evidence that such a trend has persisted at least since the 1920s. Inventories of North Atlantic water masses will be needed over approximately decadal time periods because the signatures of these changes will provide a sensitive testbed for evaluating and improving coupled ocean-atmosphere models of the climate system and for understanding the nature and causes of long-term climate change.

Session B: Existing operational experience

Real-time operational ocean forecasting in the North Atlantic at the French Navy (Abstract)

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CLS, France

Pierre Bahurel
SHOM/CMO, France

This ongoing effort started in 1991 with the design of SOAP93, a pre-operational system based on a quasi-geostrophic (QG) open ocean model of the Azores front region assimilating ERS-1 and TOPEX/POSEIDON (T/P) data with optimal interpolation (OI) technique (Dombrowsky and De Mey 1992). The SOAP93 was a mock-up, in the sense that its products were not intended to be operational. It was designed as a proof-of-concept model aimed at giving some input for the specification of a future operational system.

It has been processed from 1993 to 1996 in real-time. During this period, forecast bulletins were provided to the Navy end-users fortnightly.

The good results obtained with this preliminary system during the SEMAPHORE cruise (Eymard 1996) were the starting point of the SOPRANE project, which aims at building an operational system prototype, which is an operational system (processed routinely by Navy operators, not scientists), but not fully operational in the military sense. This system will be delivered to the Navy in April 1998. It is based on a QG model of the Northeast Atlantic, 1/10° horizontal resolution, assimilating altimeter data from ERS2 and T/P with a suboptimal linear filter SOFA (De Mey 1997).

A first release of this system has been run in summer 1997 during the ARCANE and CAMBIOS cruises, forecasts were sent to the research vessels in real-time. A good agreement between data and forecast has been obtained.

The SOPRANE follow-on system will be based on a primitive equation (PE) of the north Atlantic, 1/12° horizontal resolution. This system will be build in the framework of the MERCATOR (Courtier 1997) project, in strong collaboration with the CLIPPER project (Le Provost 1997).

Shallow Water Analysis and Forecast System, SWAFS

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SWAFS is a general purpose ocean-forecast system which is in operational or quasi-operational use for several semi-enclosed seas. The modelling system has been adapted to the Red Sea, the Persian Gulf, the Mediterranean Sea, and the Baltic Sea. Two-day forecasts of the fully three-dimensional current speeds, temperature and salinities, in addition to sea-surface heights, are made daily for each of these areas. Detailed descriptions of the Mediterranean Sea and Red Sea applications are provided by JGR articles in press. The modelling system is being systematically expanded both with respect to the domains and the capabilities of the system.

SWAFS Description

The modelling system is built around a version of a primitive equation, three-dimensional ocean circulation model commonly known as the Princeton Ocean Model (POM), which is described in its original form by Blumberg and Mellor (1997).

The model is forced with wind stresses and air-sea heat fluxes derived from Navy operational meteorological forecasts. For the Red Sea, the forecasts wind speeds are interpolated to about the SWAFS resolution using a single-layer atmospheric boundary-layer model (LABL). This allows for orographic steering by the adjacent high and complex orography of the low-level winds which is not provided by existing meteorological forecasts. BTs and CTDs, if available, are assimilated daily. A separate daily MCSST assimilation cycle is also made. Both assimilation cycles use a nudged (objective) analysis scheme. MCSSTs and BTs are available in near-real-time from separate data bases. Model execution for operational purposes is automated through the control of complex scripts.

Upgrades in progress

A substantial effort has been made to bring the POM up to more modern coding standards, specifically the conversion to FORTRAN 90. In the process the code was modified to reduce memory requirements, to improve the ability to parallelize on multiple CPU computers, and to eliminate the over indexing of many arrays.

While our existing models have horizontal resolutions between 5 and 15 km, higher resolution is needed for many nearshore areas. In order to allow this without the need for excessive computer resources, a procedure for one-way nested high resolution subdomains is being evaluated. Initial tests have been conducted for a domain in the Adriatic Sea with a resolution of 2.5 x 3 1/3 km. The plan is to be able to locate a nest relatively quickly within any of our 'host' domains. However, higher resolution near-shore domains may be crippled without the support of equivalent resolution meteorological fields.

For this reason a two-layer version of LABL is being tested. LABL runs 'underneath' the existing meteorological forecasts to use dynamics to interpolate the meteorological fields down to the resolution of the ocean model. This new version of LABL is coupled directly to the ocean model and provides air temperature and humidity in addition to wind stress.

While our existing domains have been semi-enclosed basins, we are porting SWAFS to a very large domain covering a substantial portion of the western Pacific including the South China Sea, the Yellow Sea, the East China Sea, and Sea of Japan, and the Sea of Okhotsk. Because the domain has long open boundaries, extensive data assimilation, which can only be provided by altimetric-height-derived synthetic CTDs, will be a necessity. However, these synthetic CTDs will have an uncertain reliability and may have large systematic or correlated errors. Adjustments to the data-assimilation scheme, which is a nudged objective analysis, will certainly be required.

Summary

During the process of porting the SWAFS system to several domains, the problems have largely, but not entirely, been of three basic types. They are the 1) difficulties associated with having open boundaries, 2) having insufficient *in situ* data for assimilation or having bad data, and 3) having meteorological forecast fields which are too coarse to resolve nearshore changes in surface winds, air temperatures, and humidities.

For the open boundary conditions for our Persian Gulf and Red Sea domains, we use radiation boundary conditions generally. One exception is that we provide additional control of the water elevation to stop long term draining or flooding. We also specify the salinity when there is inflow. The use of radiation boundary conditions for these basins has generally been successful, and the forecast inflow/outflow transports have been consistent with the literature.

Of the two forms of data generally available for assimilation, MCSSTs and BTs, the numbers of MCSSTs are usually adequate, while the numbers of BTs are usually insufficient. CTD profiles are relatively rare, and this hurts us where evaporation rates are high and salinities are evolving, usually in coastal regions. In the future we will be able to ingest synthetic CTDs inferred from altimetric heights, but the inferred salinities will be largely climatological and may be inadequate where there is much natural variability in the salinity fields. We also hope to eventually ingest temperature profiles from surface drifters with thermistor tails. Finally, in spite of quality control software, bad profiles can sometimes be ingested, and the only solution is to constantly monitor the forecasts.

After modelling several domains for several years, it has become obvious that the overriding requirement is to get adequate meteorological forecasts, both with respect to wind stresses and to air-sea heat fluxes. Part of the problem stems from the relatively coarse resolution of meteorological forecasts, which are much more computationally expensive than ocean-model forecasts having the same horizontal resolution. A consequence is that large gradients in the surface air temperatures and humidities, which can be the norm near land, will not be resolved. Other processes such as orographic steering or thermal driving low-level nearshore winds are also inadequately modelled. For example, we believe that the circulation patterns in the northern Levantine basin of the Mediterranean Sea are greatly affected by the orographic steering of the low levels winds by the islands of the Cretan arc, especially Crete. A second example is the observed eddy field in the Red Sea, which can be extremely complex. Again, the observed (and modelled) eddy field there appears to be sensitive to the interaction of the low-level winds with the adjacent high and complex orography. Simultaneously, the forecasts of surface air temperature and humidity fields may be in error. While the assimilation of MCSSTs can correct the errors caused by improper air-sea heat-flux rates, there is no equivalent procedure for correcting evaporation rate errors.

For these reasons, the capabilities of the SWAFS ocean forecast system are being systematically increased to allow for more accurate meteorological forcing and the assimilation of greater quantities of temperature and salinity observations.

The Forecasting Ocean Atmosphere Model (FOAM) System

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The UK Met. Office has developed an ocean data assimilation system which is being used for three applications:

a) real-time analyses and forecasts of the deep ocean out to 5 days ahead for the Royal Navy
b) analyses of the tropical oceans for seasonal forecasts
c) assimilation of historical data for climate forecasts up to 10 years ahead.

This article focuses on FOAM - the Forecasting Ocean Atmosphere Model - which is designed for the real-time application. Section 1 describes the FOAM system and its current status. Section 2 describes the steps taken to assess the FOAM system's performance and its ocean model's systematic errors. Section 3 briefly reviews the "operational" systems for monitoring the oceans which have been developed at other centres. The final section outlines plans for further development of FOAM.

Description of FOAM system

FOAM is now producing analyses and short-range forecasts of the ocean interior, on a one degree global grid, routinely in real-time. It presently runs daily as part of the Met. Office operational suite on the Cray C90 computer and has been implemented in the new suite on the Cray T3E. Output will be transmitted to the Royal Navy at Northwood in GRIB format for visualisation and manipulation on the forecasters' workstations.

The FOAM model is based on the Bryan-Cox ocean model and includes parameterisations of the mixing of tracers and momentum in the near surface mixed layer and a sea-ice model. It is driven by 6-hourly mean surface fluxes from the Met. Office NWP system. Surface temperature data (from ships, buoys and the AVHRR satellite) and thermal profiles received in near real-time are assimilated into the model by a scheme similar to that currently used by the NWP system (Lorenc *et al.,* 1991). The observations are quality controlled using the Levitus (1994) climatology or the previous analysis. They are assimilated over a period of 5-10 days using a forecast error correlation scale of 300 km in most areas. Alves *et al.,* (1995) describes fully the prototype FOAM system, which ran from August 1994 to November 1996.

Assessments of FOAM

Statistics on the differences between the analysis and observations are calculated routinely and compared with similar statistics for the Levitus climatology. Movie loops and monthly means of the fields and their differences from climatology are also calculated routinely to enable the performance of the system to be assessed. Statistics from the pre-operational system indicate that FOAM is generally closer to independent observations than the climatology to at least 300 metres depth.

Independent integrations of the model which do not assimilate data and are driven by monthly climatological fluxes have also been performed. Starting from the Levitus climatology at rest, they develop large differences from the climatology over the first few months of integration. Cooling of the upper 100-300 metres just to the east of the Flemish Cap, and weakening of the barotropic circulation of the middle of the N. Atlantic sub-tropical gyre after its initial spin up are particularly noticeable. These biases are discernible in the analyses.

Forbes (1995) investigates the extent to which the thermal profile and surface temperature data are able to compensate for these systematic errors and uncertainties in the fluxes (Figure 1). Bell (1997) examines the representation by the model of the torques driving the depth integrated flow (Figure 2). Finally, as a first step towards assimilation of historical observations, all the observations used by Levitus *et al.,* (1994) to build their climatology have been assimilated into the FOAM model, regardless of the year when they were made, to form a seasonally varying climatology. The increments made using the observations give a good indication of the model's systematic errors; if the model and fluxes driving it were perfect the increments would be negligible.

Other operational systems for monitoring the deep ocean

The US Navy's OTIS system has produced daily global analyses of the ocean's thermal structure for a number of years (Clancy *et al.,* 1992) and the Australian BMRC has also produced subsurface thermal analyses on a routine basis since 1988 (Smith 1995). Systems to assimilate oceanographic data on a regular basis into ocean general circulation models forced by wind stresses from numerical weather prediction systems, for monitoring of the equatorial oceans or seasonal predictions, have been pioneered by NCEP (Ji & Smith 1995) and Kimoto *et al.,* (1997) and have been or are now being implemented in several centres (e.g. ECMWF). A few systems have also been developed for prediction of mesoscale motions. SOAP (Dombrowsky and de Mey 1992) produces forecasts for the Azores frontal region, HOPS (Robinson *et al.,* 1995) is a system designed to be relocatable and applicable to regions with strong currents and steep bathymetry, and Smedsted *et al.,* (1997) have developed a 1/8° model for the Pacific ocean which assimilates altimeter data and is being transitioned to operational use at FNMOC.

Plans for Future Development of FOAM

The main focus for development of FOAM in the next two years will be to implement high resolution limited area nested models of the North Atlantic within the global FOAM system and to assimilate into the model any altimeter data of sufficient quality which can be made available within a couple of days of real-time. Further development is likely to be the more effective if there is collaboration with other groups in a number of areas: model and data assimilation intercomparisons such as Roberts *et al.,* (1996) and the DYNAMO and DAMEE are very valuable; the potential for collaboration on the development of a more sophisticated system with the Mercator project is being explored; the GODAE experiment would serve as a focus for collaboration in the development and intercomparison of operational systems.

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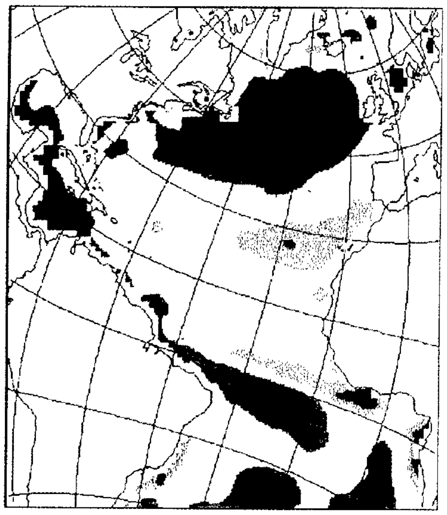
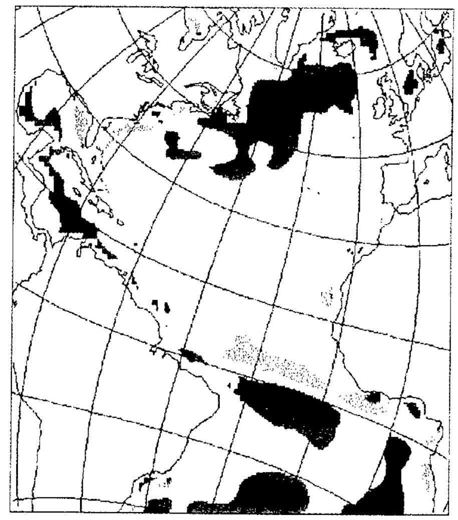
Bell Fig 1

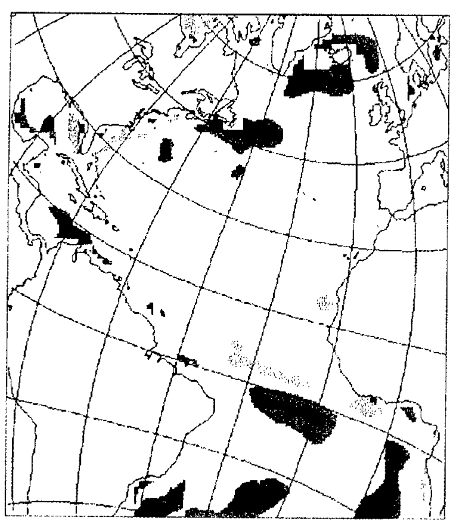
Sea surface temperature anomaly from Levitus Climatology for 15th September 1993



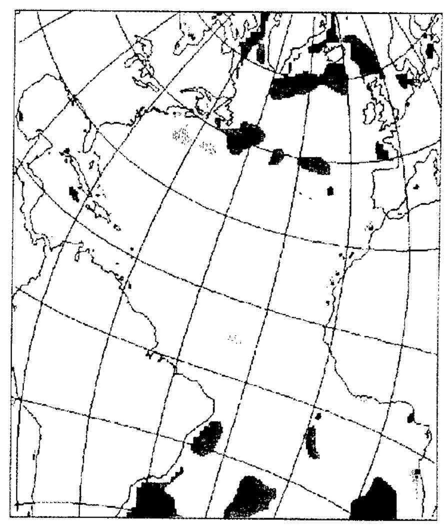
Model - Climate



Assim. - Climate
SST at the surface



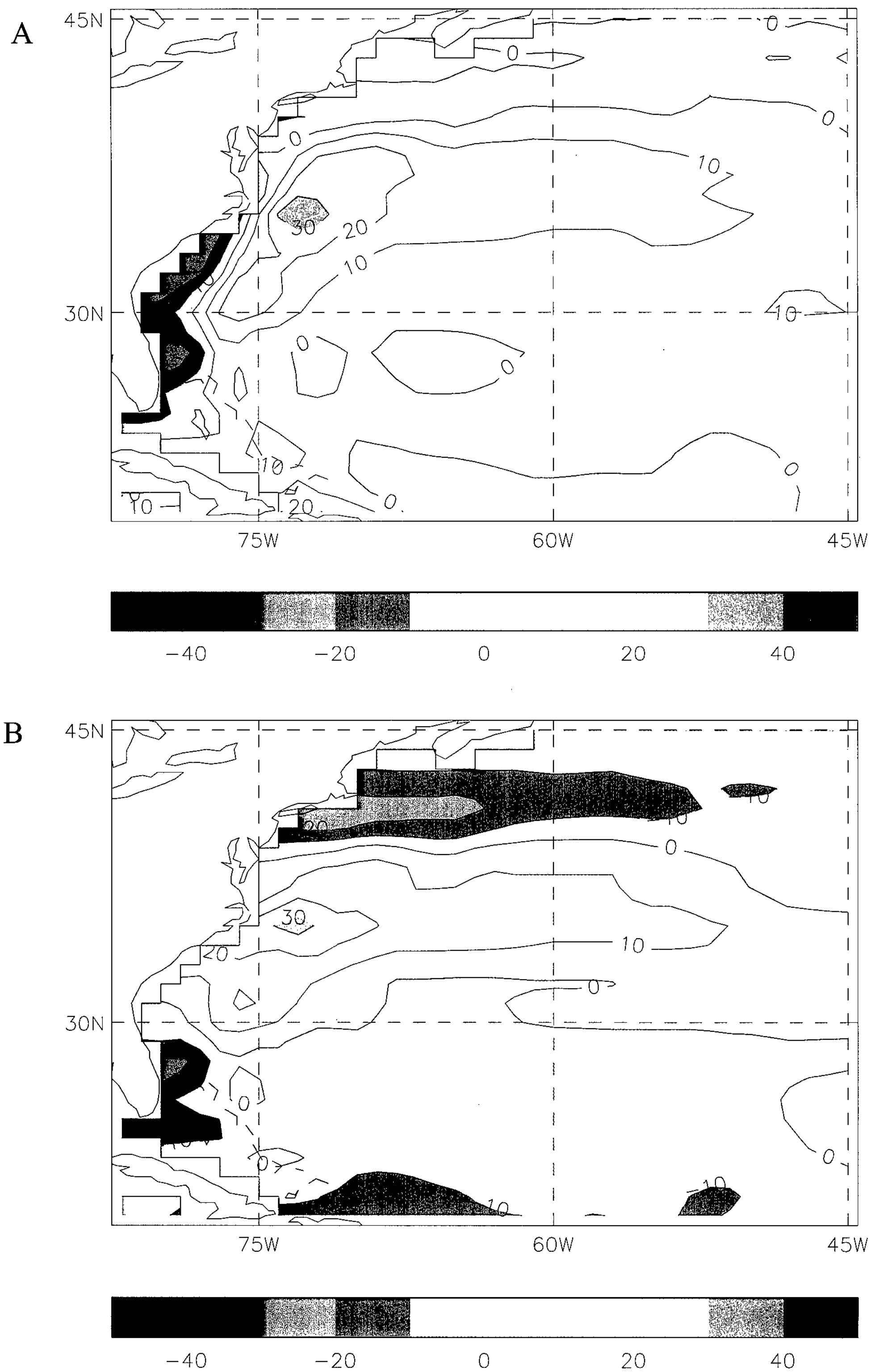
Assim. - Climate
SST through mixed layer



Op. Analysis - Climate
Surface analysis, no model

Figure 2

The contributions to the barotropic streamfunction driven by (a) the bottom pressure torque and (b) the vortex stretching at the top of the topographic steps. In a quasi-geostrophic model the two contributions would be the same
The contour interval is 10 Sverdrups



Operational sea state forecasting at ECMWF

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1. Introduction

A brief overview of the operational wave forecasting system at ECMWF will be given. Presently, we run the WAM model (Komen *et al.,* 1997) on two domains, one for the globe with a resolution of 55 km and one for the Mediterranean and the Baltic with a resolution of 0.25 deg. The forecast period is 10 days. Optimal initial conditions for the global model are obtained by assimilating Altimeter wave height data from ERS2.

The operational results are verified extensively on a routine basis. Analysed and forecast wave fields are compared against buoy data, first-guess wave height fields are verified against Altimeter data, while forecast wave height fields are compared with analyses. Some results of this verification will be presented. For example, for the North Atlantic we find a typical forecast skill of about 5 days, while, because of the dominance of swell, the forecast skill in the tropics may reach 7-8 days. Finally, we give an example of how a model can be used for quality control of wave observations.

2. Operational wave forecasting

At ECMWF we run the third-generation WAM model on two domains using surface winds from the T213/L31 version of the ECMWF's atmospheric model. The first application is for the Mediterranean and the Baltic. The resolution is 0.25 deg on a regular lon-lat grid. The wave spectrum has 25 frequencies and 24 directions. Shallow water effects are included.

The second domain is the globe. The resolution is 55 km and the grid is an irregular lon-lat grid. It has a regular spacing in the meridional direction but an irregular spacing in the zonal direction in such a way that along a latitude the distance between grid points remains constant when going to the poles. This irregular grid is needed to maintain large advection time steps and in addition it gives a saving of memory of about 25%. The spectrum has 25 frequencies and 12 directions. Shallow water effects are important for the coastal areas and are therefore included. The bathymetry was obtained from a smoothed 15"x15" topographic data set. We will concentrate here on the global application.

At ECMWF we have the following operational, daily cycle. A one day analysis using ERS-2 Altimeter wave height data is followed by a 10 day forecast using ECMWF's surface winds. The analysis of wave height is done by means of an optimum interpolation method while dynamical constraints are used to generate an analysed wave spectrum (Lionello *et al.,* 1992). Output and archiving of 12 integrated parameters for total sea, wind sea and swell is done every 6 hours. In addition, we output 2 dimensional spectra and we archive the 12 Z analysed spectra. This gives a total IO of about 3 Giga bytes per day.

The WAM model has been reprogrammed so that it can be run on a memory distributed system. Presently, the model is run operationally on 4 processors of a Fujitsu VPP-700. Elapse time for the daily cycle is about 50 minutes. The model scales fairly well with increasing number of processors. For example, on 16 processors we still achieve a speed up of about 95%.

3. Verification and data studies

We have performed over the past 5 years extensive validation studies of analysis and forecasts of our wave forecasting system. Analysed wave fields are verified against buoy data, first-guess wave fields are verified against Altimeter wave height data, while forecast wave height is verified against buoy data and wave analysis. A more detailed account can be found in Janssen *et al.,*(1997).

3a. Forecast verification against analysis

At ECMWF we try to asses the value of a forecast against information that is readily available. In our case we use the wave height and surface wind speed climatology as a yardstick. We therefore use the anomaly correlation score which is the normalised correlation between forecast and analysis

anomaly with respect to the climate. Studying these scores over the past few years we have concluded that

1. There is larger skill in wave height than in wind speed. This is caused by the swell component of the waves which has a large memory.

2. There is larger skill in swell dominated areas such as the Tropics than in wind-sea dominated areas such as the North Atlantic.

3. But the forecast skill in the North Atlantic is still in the order of 5 days.

3b. Verification of first-guess against Altimeter wave height

By comparing modelled wave height with Altimeter data we have learned a lot about the quality of the first-guess wave height field, which is quite good since presently the standard deviation of error is about 40 cm. However, wave heights from the Altimeter tend to underestimate the true wave height, in particular for young windseas. The underestimation of wave height by the Altimeter follows from a comparison of Altimeter wave height with buoy data.

The problem with the Altimeter is probably related to the assumption of Gaussianity used in the Altimeter wave height retrieval algorithm. This assumption is only valid for gentle, not-too-steep ocean waves. And indeed, when comparing Altimeter wave height data with modelled wave heights as function of wave slope, the Altimeter wave height bias is negative and is seen to increase with slope.

As a consequence, a wave analysis system that uses Altimeter data will, assuming an unbiased model, underestimate wave height in particular for windseas(which are steep).

3c. Validation of analysis and forecast against buoys

Traditionally, there have been extensive efforts to validate the wave height analysis against buoy data. Comparing relative errors (which is the normalised standard deviation of error, also called scatter index) over the past 15 years reveals that there are steady improvements in the modelling of surface winds and wave height since the relative error has decreased from about 30 % to 20 %. Timeseries of modelled wave height bias show underestimation of wave height for windseas which is caused by the Altimeter wave height data assimilation. By comparing bias time series from different areas it is even possible to perform quality control of observations. An example is the bias time series for the North-east Atlantic which behaved rather anomalously when compared with the corresponding time series from other areas. After corrective action by the data producers the performance of the North-east Atlantic buoy network returned to normal.

Finally, buoy data can also be used to asses the merits of the wave forecasts, although due the distribution of the buoy network the value of this comparison is rather limited. Nevertheless, these buoy data have provided useful information in a comparison exercise between different forecasting centres, revealing the weak and strong points of the different wind and wave forecasting systems.

4. Conclusions

As can be seen from the previous discussion we have reached a fairly mature state of affairs regarding sea state forecasting. Extensive use of conventional and satellite data is being made for (i) specifying the wave analysis and (ii) for verification purposes, and wave model results may be used for quality control of the observations.

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Real-Time Current Measurements and Operational Current Forecasting in Support of Atlantic Slope Deep Water Engineering

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Abstract

Since 1987, GEOS Limited, and its predecessor, Wimpey Environmental Limited, have been measuring oceanographic parameters along the European continental slope. The work has been undertaken on behalf of various oil and gas companies in support of exploration and field development. This paper reviews some of the principal activities associated with deep water engineering and shows how provision of oceanographic information in real-time can assist in decision-making offshore. Recent developments in empirical forecasting of site-specific current velocity are also discussed.

Introduction

The European Atlantic Frontier region represents an area of intensive oil exploration and field development. The major interests lie on the continental slope, in water depths of between 300 and 1200 metres. This is a region of very complex oceanography where currents can be strong and highly variable. Operationally, there are many requirements for current information such as for vessel selection, station-holding, ROV operations, riser deployment and ship loading. For design purposes, detailed knowledge of currents is necessary to assess operability and extreme loadings on floating production systems.

GEOS has worked closely with BP and other operators during the exploration and development of the Atlantic Frontier region, providing detailed information on current conditions. The fast-track approach to development of the Foinaven field and other subsequent activities have stimulated the requirement for enhancements in the acquisition, analysis, dissemination and management of current information. Some of these developments are described in the following sections.

Engineering requirements for oceanographic information

This section provides a brief overview of various maritime engineering functions and their respective requirements for metocean information.

Offshore Seismic Exploration

The principal metocean conditions which affect seismic exploration are sea state and near-surface current velocity. Sea state limits the conditions in which the vessel can deploy and recover sources and streamers, and introduces acoustic noise and positional uncertainty into the acquired data. Surface current velocity can displace the streamer from its intended line. Water level data may also be required for the reduction of geophysical data.

Exploration Drilling

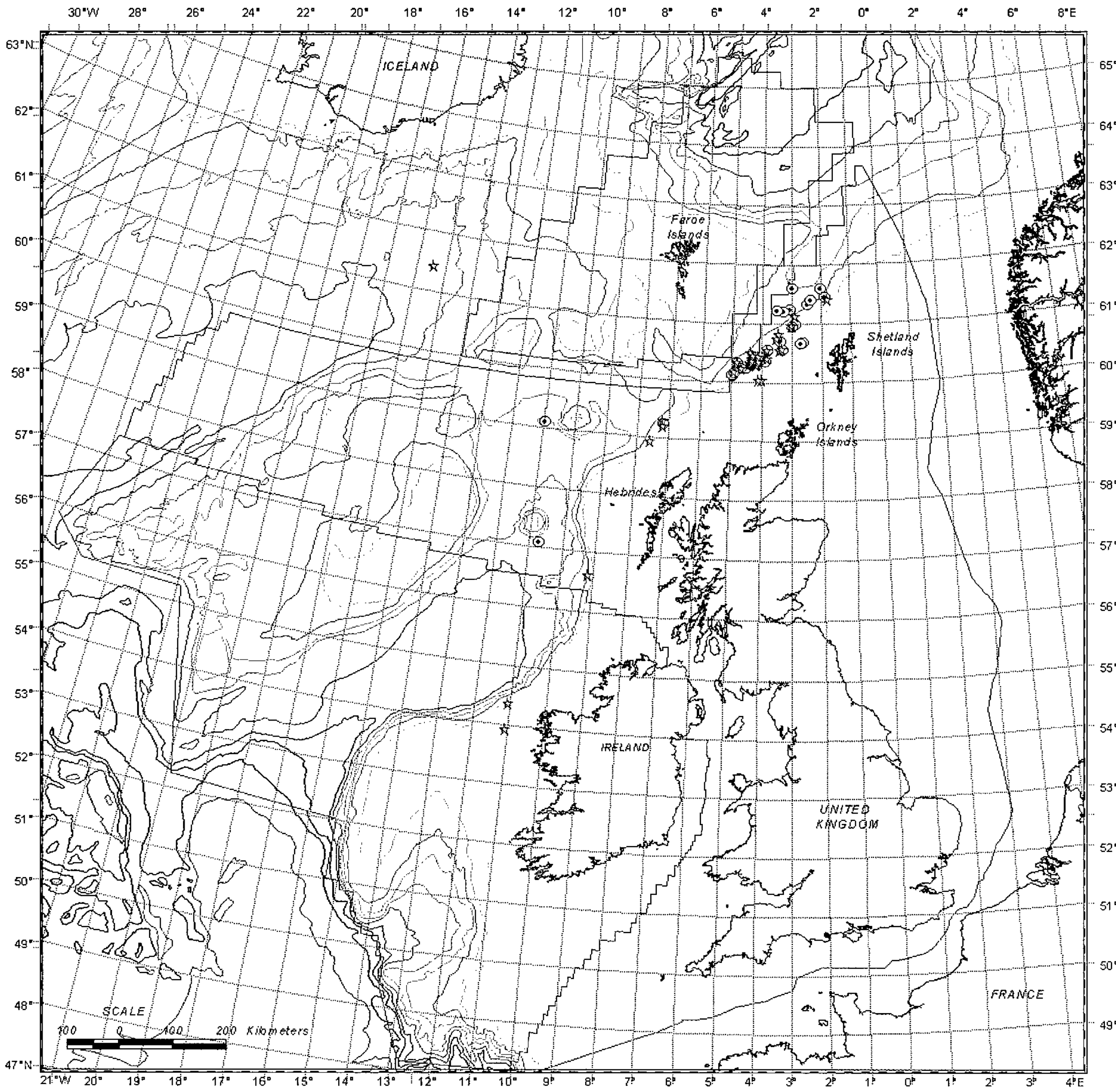
Current velocity, wind and wave conditions are the principal metocean factors affecting exploration drilling. In deep water, ocean current imposes major stress on the subsea drilling components, and is a principal parameter in riser design. Environmental conditions affect rig selection, drilling methodology and optimal drilling season to minimise operational down-time.

Offshore Operations

Winds, waves and current velocity are the principal metocean factors affecting offshore operations. For operational planning and optimisation, metocean statistics are required to describe typical and worst-case conditions by month, allowing assessment of potential downtime. For on-going operational support, real-time provision of metocean measurements and forecasts are required.

Floating Production Systems

These are of increasing importance in the development of marginal and deep-water fields. The response of the vessel and mooring system



UK Atlantic Margin Showing Locations of Current Data Measured by GEOS

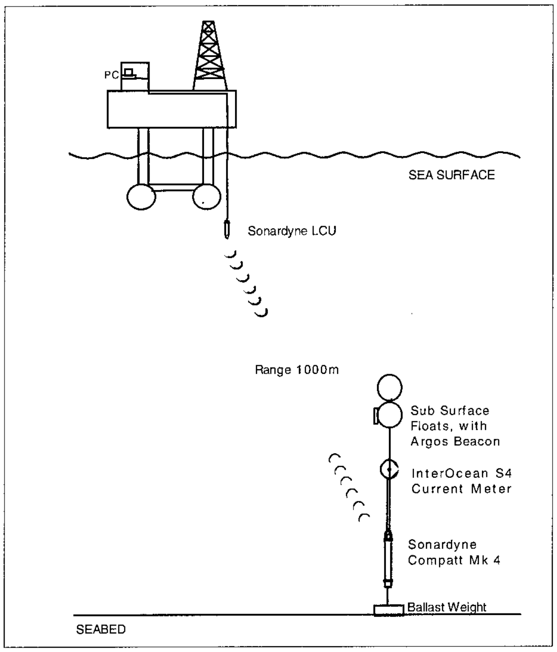
to combined environmental forces may be extremely complex. In the design case, many permutations of current, wave and wind loadings may need to be considered, with particular regard to long period wave excitation and the occurrence of winds, waves and current from different directions. For FPSOs (Floating Production, Storage and Offloading facilities), operability and down-time due to adverse metocean conditions are of major importance in terms of system viability. In deep water fields on the continental slope, current conditions may be strong and variable, imposing stress on risers and mooring components.

Data inventory

GEOS holds secure archive copies of oceanographic data sets, on a confidential basis, on behalf of various offshore operators, both West of Shetland and world-wide. In general, knowledge of ocean data (location, dates, instrumentation etc.) collected on behalf of individual organisations is freely available, but the actual data remain confidential to the owner.

Real-time seabed current monitoring

In the development phase of a deep water field, there are specific engineering requirements for knowledge of near-bed currents in real-time. Stimulated by BP's requirements, and in collaboration with Sonardyne Limited, GEOS developed a system for acoustic telemetry of data from a near-bed moored current meter to a command unit deployed from a surface ship or semi-submersible.



Deployment Details of Real-Time Seabed Current Monitoring System

An Interocean S4 electromagnetic current meter is interfaced to a modified Sonardyne Compatt acoustic release unit. Encoded data are then telemetered acoustically. At the surface, an LCU hydrophone receiver unit is suspended over the side of the rig; this receives the telemetered near-bed data and connects via a cable to a PC in the vessel control room. This system allows display and logging of near-bed conditions to a surface PC. A simple real-time display shows current speed, direction, sea temperature and salinity, both graphically and as clear numeric values. Measurements are made once every ten minutes. At the seabed end the three most recent 10-minute measurements are stored in a buffer, encoded and then repeatedly transmitted until they have been received successfully by the surface command unit.

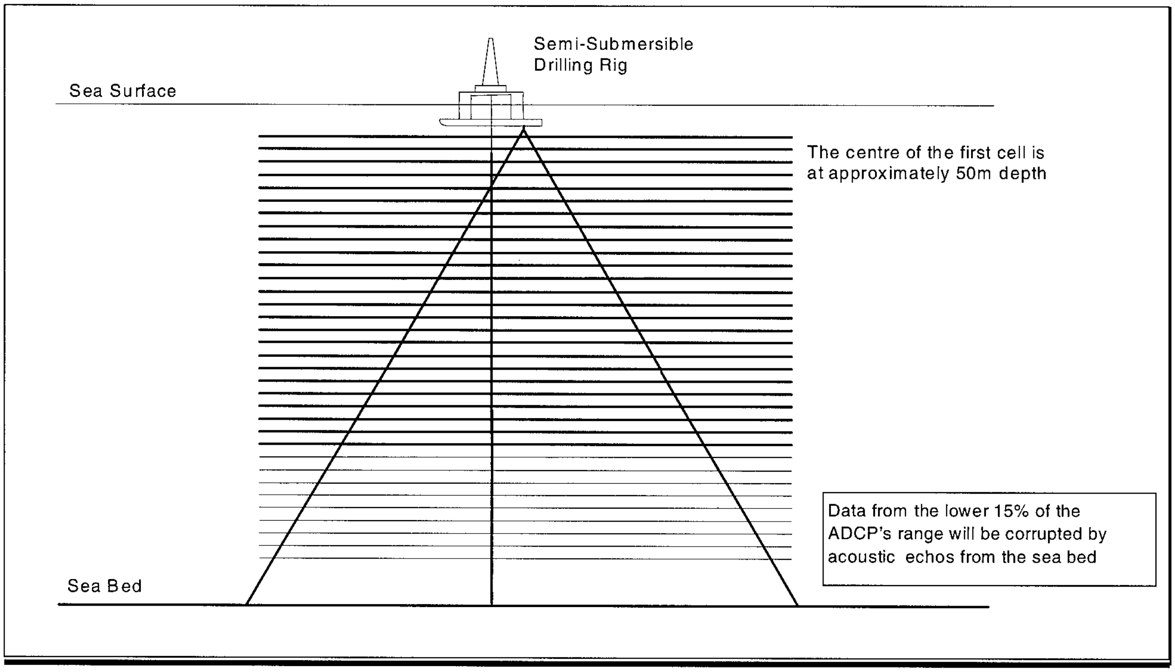
Real-time current profile measurements

GEOS provides real-time current profile measurement systems to support deep water drilling activities. The measurement system comprises a low frequency Acoustic Doppler Current Profiler (ADCP) suspended just below the vessel hull. This is connected by cable to PC situated in the vessel control room. GEOS' software suite RIGADCP provides two-way communications with the instrument, a versatile series of screen displays of current data and also data storage to disk.

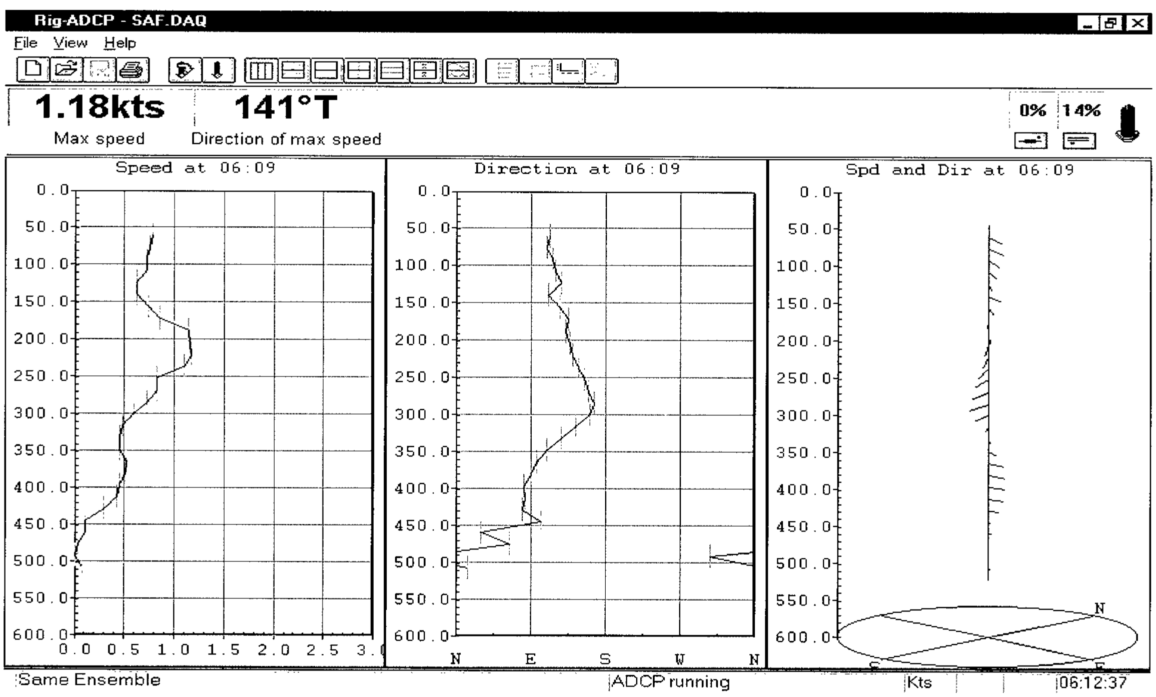
Many successful deployments of this system have been undertaken by GEOS, primarily in the Atlantic Frontier region, Vietnam, Malaysia and Indonesia. To date, more than twenty five instrument years of data have been collected, on behalf of a number of offshore operators.

A profile of current velocity is measured remotely from the ADCP suspended just below the drilling vessel. The measurement range is a function of the transmission frequency of the instrument. A low frequency 75 kHz ADCP can achieve a range of approximately 700 metres in optimal conditions. Range is influenced by a variety of factors such as background acoustic noise, scatterer density and water temperature and salinity.

In normal operational mode, RIGADCP is set up to acquire current velocity profiles once every 10 minutes, for a series of measurement cells of 16 metre length. The figure above shows the measurement geometry of a typical deep water RIGADCP deployment. The principal limitations of the system are first that it does not provide measurement in the top 50 metres of the water column, and secondly that it does not provide measurements in the bottom 15 percent of the water column due to acoustic interference with the sea bed.



Real-Time ADCP Current Profile Monitoring System - Measurement Geometry



Real-Time Current Profile Display from Rig-Based ADCP System

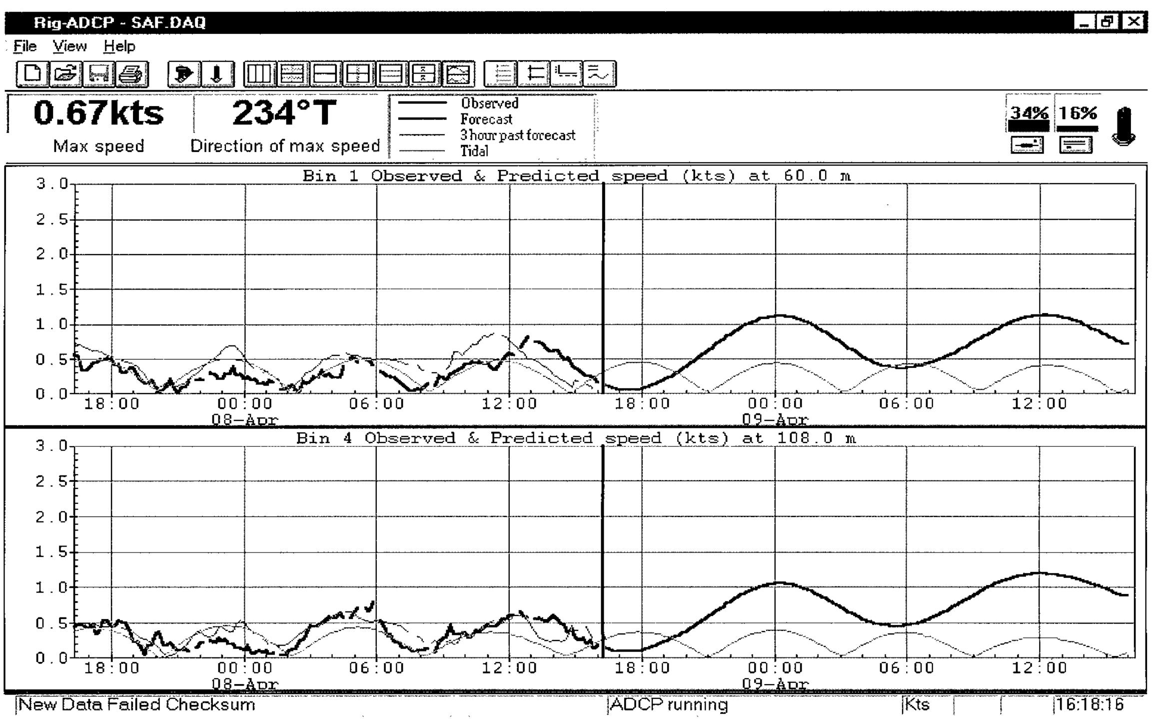
GEOS' RIGADCP package provides the user with a series of readily-interpreted graphical views of the measured data. The instantaneous profile plot, shown above, illustrates measured current speed and direction in each depth cell, and also clear numerical display of the maximum current speed through the water column. This screen is of particular interest to ROV operators. Other screen options include short- and long-term time series displays at selected depths.

During field development, there will typically be a number of semi-submersibles and surface ships working in close proximity, performing different engineering functions, each with requirements for knowledge of current conditions. GEOS developed radio telemetry transmission of current data collected at the central location, such that a receiver unit and PC could be installed on each 'satellite' vessel which required knowledge of current conditions. Thus each satellite station could have access to the full variety of data views provided within RIGADCP.

Empirical short-term current forecasting

GEOS has developed a short-term current forecasting system, ADCPPRED, which can be used to predict current speed and direction, through depth, over the forthcoming 24 hour period. ADCPPRED is a PC-based software package which is used in combination with RIGADCP.

Extensive numerical analysis was undertaken on previously-measured West of Shetland current profile data. Harmonic analysis was used to determine the predictable tidal component of flow, and then empirical pattern-recognition techniques were developed to estimate the highly-variable non-tidal component of flow. The non-tidal flow comprises a persistent north-easterly ocean current component, intermittent passage of eddies and various high-frequency effects. The approach taken with ADCPPRED was to provide a robust empirical prediction procedure rather than to attempt a full hydrodynamic interpretation of the available data. During the development phase, various prediction algorithms were tested on past data to assess how well they would have performed in real-time. The preferred scheme was then encoded into a real-time software application.



Display of Real-Time Current Predictions in Time Series

RIGADCP provides the user with an easily-interpreted graphical display (see page 43) showing time series at two selected depths through the water column. To the left of the centre line, current speeds measured over the last 24 hours are shown, together with past predictions which were made N-hours before each measured data point. The N-value is selected by the user; comparison between measurements and past predictions provides an indication of how well the prediction scheme is working at the present moment in time. To the right of the centre line, predicted current for the next 24 hour period is displayed. This is shown for the predictable tidal component (faint line) and also for the total current (heavy line) which also includes all the variable non-tidal effects.

The current prediction software has now been operational offshore since November 1995. Since its initial installation, various refinements have been made to improve the quality of the forecast and to optimise the form in which the information is displayed to the decision-maker.

ADCPPRED now provides an effective tool to support operational planning offshore and will continue to be developed and refined by GEOS.

Conclusion

The current measurement and metocean data management systems described in this paper have been developed progressively over the last ten years to meet the needs of offshore exploration and field development requirements. Significant enhancement and further development has been stimulated as a result of the fast-track Atlantic Frontier programme. Current velocities are strong and highly variable in the deep waters of the continental slope West of Shetland and can impair offshore operations very significantly. The ability to acquire, display, interpret and disseminate current information in real-time can assist greatly in operational planning, resulting in safe working and potentially large cost savings. A by-product of real-time current measurement systems is the emergence of a large volume of data for use in the derivation of operational and extreme design environmental statistics.

Acknowledgements

GEOS gratefully acknowledges the support and encouragement of BP, and particularly Dr Colin Grant, during the development and application of offshore measurement practices in the Atlantic Frontier region.

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Session C: Definition of goals for civilian forecasting

Data assimilation for North Atlantic forecasting (Abstract)

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This paper will discuss the components of an operational data assimilation system which currently is being implemented for the North Atlantic and the Nordic Seas. The physical model is an isopycnic model based on the Miami Isopycnic Co-ordinate Ocean Model (MICOM), while the ecosystem model is an implementation of the Fasham *et al.* model. The model system is capable of simulating the annual variability and circulation in the North Atlantic and the Nordic Seas for the physical and the marine ecosystem variables. An operational system must include efficient data assimilation methods for the integration of information from observations with the models. Clearly, an operational system will to a large extent have to rely on observations from earth observations satellites. Examples of data sources are SST and SSH data which can be assimilated into the physical model, and chlorophyll concentrations derived from ocean colour data which can be assimilated in the marine ecosystem model. There is a huge amount of information collected from the ocean surface or upper ocean, while data available on a regular basis from the deep ocean is almost non-existent. This implies that the data assimilation system must be capable to project the surface information into the deep ocean in a consistent manner. The Ensemble Kalman Filter (EnKF) is a promising method which is capable of estimating consistent vertical influence function and to provide a balanced multivariate analyses, and some preliminary examples from this method will be presented.

Real-time operational forecasting and ocean observing and predicting systems research in the Atlantic Ocean and Mediterranean Sea (Abstract)

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Technical and scientific activities in the sea require a knowledge of the spatial distributions of oceanic state variables and their time dependencies. The determination of such distributions in three spatial dimensions and time is called field estimation. In general, there is a requirement for a knowledge of physical, biological, chemical, acoustical, and optical variables. Accurate and efficient estimation of these four dimensional interdisciplinary fields in the ocean is essential. Field estimates via data assimilation meld observations and dynamics and provide an efficient means of representing the physical processes which influence biogeochemical, ecological, acoustical and other processes in the sea.

The realistic estimation of oceanic fields and the use of such fields in interdisciplinary research and practical operations and management is now feasible on a substantial basis as a result of the advent of ocean observing and prediction systems. Such systems produce nowcasts, forecasts and data-driven simulations by melding dynamics and observations via the assimilation of measurements into numerical models. The Harvard Ocean Prediction System (HOPS) is a flexible, portable and generic system for nowcasting, forecasting and simulations. Components include synoptic and climatological data analysis and management algorithms, statistical models including multiscale feature models, flexible assimilation and initialisation schemes, an interdisciplinary dynamical model hierarchy, and a general application module set. Recent advances in methodology and research and operational applications of HOPS are illustrated by examples, including: forecasting and simulations of shelf/slope frontal variability (Shelf Break Primer), real time forecasting at sea of physical and biological variables (Plankton Patchiness Studies by Ship and Satellite), sustained real time operational forecasts for naval exercises in the Ionian Sea (Rapid Response 97), combined biological and physical data assimilation (BIOSYNOP and GEOSAT), hindcasting and forecasting of physical and biological variables for fish dynamical models for management purposes (Advanced Fisheries Management Information System (AFMIS)), etc. HOPS is a central component, of a co-operative project among 12 theoretical, modelling, observational and applications groups, for the development of the scientific and technical conceptual basis of a generally applicable, advanced coastal system, the Littoral Ocean Observing and Predictive System (LOOPS).

Assimilation of remote-sensing data in high-resolution models of the North Atlantic: Current research and prospectives

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Abstract

Very few advanced assimilation systems have been implemented into ocean models resolving the mesoscale flow field at the scale of an ocean basin. Several questions arise with respect to the EuroGOOS North Atlantic community: do we need an assimilation system which can take proper account of error statistics? Do we need to simultaneously assimilate all components of the observed signal, including mesoscale, seasonal and interannual processes? Do we need to implement such a system over the whole Atlantic basin, or in regional sub-models ? To investigate these questions, we present an overview of assimilation activities conducted at LEGI, Grenoble, emphasising on the elements which could contribute to the development of an operational assimilation system based on remote-sensing observations.

The SEEK (Singular Evolutive Extended Kalman) filter is a new data assimilation scheme developed at LEGI, which properly propagates the error statistics with time. The SEEK filter combines the concepts of Kalman filter, order reduction, and ensemble forecasting. The scheme has been implemented in a variety of ocean systems. In this note, we identify the situations in which the scheme works properly, and the implications of that for ocean observing systems.

Introduction

Very few advanced assimilation systems have been implemented into ocean models resolving the mesoscale flow field at the scale of an ocean basin. By 'advanced scheme', we mean an assimilation system which properly combines observations and model dynamics, taking into account the error statistics and propagating this information with time. We consider the following questions: Do we need an assimilation system which can take proper account of error statistics, or should we be satisfied with an empirical scheme? Do we need to simultaneously assimilate all components of the observed signal, including mesoscale, seasonal and interannual processes, or can we consider these processes separately? Do we need to implement such a system over the whole Atlantic basin, or is it relevant to design assimilation systems in regional sub-models? The answer to these questions depends on three elements at least: the capacity of existing assimilation schemes, the degree of scientific and technological progress which we can expect for the future, and the requirements expressed by the customers of operational oceanography. In the context of EuroGOOS North Atlantic community, we examine the research pathway of the Grenoble Group with the aim to identify the capacity and limitations of a number of assimilation systems based on remote-sensing observations.

The genesis of an assimilation system

The Grenoble Group has developed a suite of assimilation schemes for ocean circulation models. The degree of sophistication of the methods is very wide, as the schemes include nudging, optimal interpolation, simplified Kalman filters and the variational-adjoint technique. A number of schemes have been developed at the research level only, while others have been implemented in practical oceanographic situations.

In the SIMAN project (Simulation de l'Atlantique Nord), the nudging approach has been used to assimilate altimetric observations in a high-resolution (1/6° resolution on the horizontal, and 6 layers on the vertical) quasi-geostrophic model of the North Atlantic basin between 20°N and 60°N. The method has been successful in reproducing synoptic features of the ocean circulation observed from satellites, and the SIMAN system has been further validated by conventional instruments (Blayo *et al.*, 1997; Brasseur *et al.*, 1996). However, the method is largely sub-optimal and does not provide estimates of the error left in the assimilated fields. A similar assimilation scheme has been implemented in the MOCA project dedicated to the modelling of the South Atlantic circulation (Florenchie and Verron 1997).

In the IDOPT project, an optimal method has been developed for an idealised QG model of the Gulf Stream system that resolves the mesoscale eddies, using the strong constraint variational method to reconstruct an ocean trajectory in the framework of twin experiments (Luong *et al.*, 1997). This approach allows to identify the true ocean very well in spite of the non-linearities of the model dynamics, but the cost of the minimisation scheme prohibits the blind use of such method in a realistic ocean model. Similar conclusions are expected from the application of variational methods to more complex primitive-equation models.

The development of a new scheme based on sequential estimation theory was motivated by the advantage of an assimilation system that admits a hierarchy of simplified versions, while keeping the properties of a solid statistical framework. The genesis of the assimilation system developed in the Grenoble Group is illustrated in Table 1.

The genesis of an assimilation system

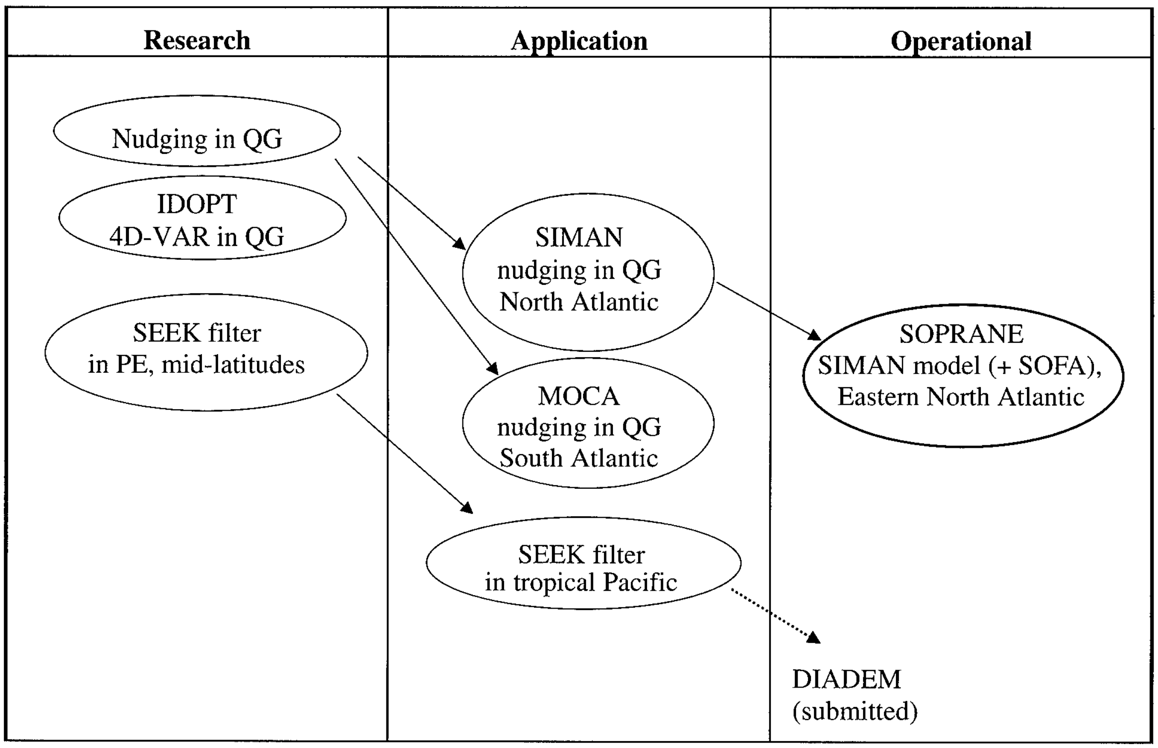

Table 1. Assimilation projects at LEGI

The SEEK filter

Basic concept

A new data assimilation scheme derived from the Kalman Filter has been elaborated at LEGI for ocean circulation models, which relies on the concept of order reduction (Pham 1996, Brasseur *et al.*, 1997; Pham *et al.*, 1997). In order to reduce the dimension of the assimilation problem, the initial error covariance matrix is represented by means of a truncated series of orthogonal perturbations. The orthogonal sub-space is determined so as to capture the dominant modes of variability of the model dynamics.

The algorithm has been formulated in quite a general fashion to make it tractable with a large variety of ocean models and measurement types.

The initial motivation for developing the so-called Singular Evolutive Extended Kalman (SEEK) filter was to control the mesoscale activity of mid-latitude oceanic flows using altimetry and thermal imagery, investigating how well surface observations of the ocean can be used to reconstruct the time evolution of eddy fields.

Numerical experiments

The SEEK filter has been implemented to assimilate altimetric pseudo-observations in non-linear, primitive equation models that use either the density (MICOM) or the pressure (SPEM) as vertical co-ordinate. A simplified box configuration has been adopted to simulate a Gulf Stream-like current and its associated eddies with a resolution of 20 km on the horizontal, and 4 or 11 levels on the vertical. The privileged directions of error propagation are evaluated from a three-dimensional, multivariate EOF analysis of model states obtained from prior historical simulations.

In a first series of twin experiments, we compare a steady-state approximation of the SEEK (in which the reduction operator is kept constant with time) with the evolutive version of the filter (in which the reduction operator evolves during the assimilation according to the model dynamics).

The cost of the stationary filter is only a few percent of the cost needed for the model integration; by comparison, the cost of the evolutive filter is approximately equal to that of "r" model integrations, where r is the dimension of the reduced space (r ~ 100 in the present experiments).

The assimilation statistics demonstrate the capacity of both versions to reset the model trajectory in the vicinity of the true field with the provision that error statistics are correctly specified. By contrast, the error reduction is substantially altered if the error sub-space is initially inconsistent with the actual error statistics (Fig. 1).

Using consistent error statistics, the filter is shown particularly efficient to control the velocity field in deep layers using surface observations only: the horizontal and vertical extrapolation of altimetric measurements is performed according to the three-dimensional structure of the reduced space.

However, the progressive degradation of the assimilation statistics is observed with the steady state filter as the assimilation proceeds. This result is partly explained by the existence of growing components of the error which are not captured by the reduced space. The evolutive filter, however, is able to maintain the estimation error at low level without producing the slow drift observed on Fig. 1.

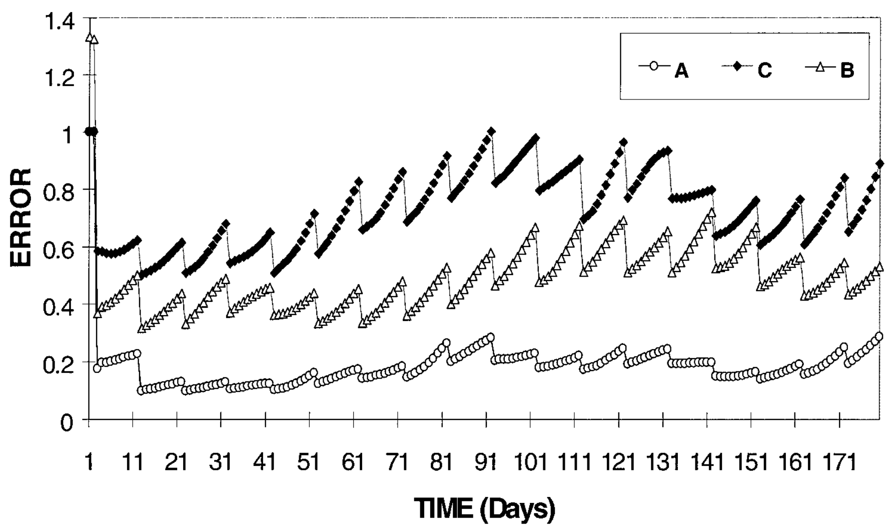

Figure 1. *RMS statistics of sea-surface height using the stationary SEEK filter (MICOM PE model). The results of three assimilation experiments are shown, using excellent, intermediate and inconsistent error statistics. The "**A**" curve is obtained with a reduction operator consistent with both the pseudo-observations and the true initial state; the "**B**" curve corresponds to a reduced space inconsistent with the initial state and consistent with the pseudo-observations; the "**C**" curve corresponds to a reduced space consistent with the initial state and inconsistent with the pseudo-observations.*

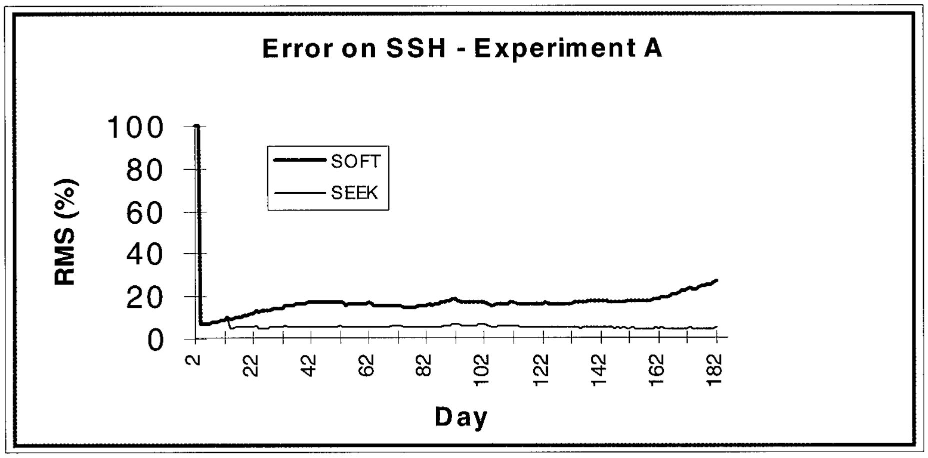

Figure 2. *Evolution of the assimilation error during two experiments in which the first guess error is correctly specified: comparison between the evolutive (SEEK) and the steady-state (SOFT) filter in a reduced basis of 10 modes only.*

Additional experiments are conducted to examine the performances of the filter when the initial error covariance is correctly specified by a strongly reduced basis. The dimension of the reduced space can be taken very small (10 modes in the present experiment) provided that it contains the 'true' components of the error at the initial time. The results show the capacity of the evolutive filter to correctly propagate the statistical information forward in time. By contrast, the steady state scheme in similar experimental conditions exhibits the progressive degradation of the filter performances (Fig. 2).

Conclusions

The Grenoble Group has developed a suite of assimilation systems with the aim to serve the purposes of (i) scientific research and (ii) operational ocean forecasting systems (e.g. the SIMAN project). This scheme has been implemented in the Tropical Pacific Ocean, assimilating Topex/Poseidon altimetric observations to reconstruct the history of seasonal events from 1993 to 1995 (Verron *et al.*, 1997). A project has been recently submitted to the European MAST programme to further validate the SEEK filter and to develop a pre-operational assimilation system of the North Atlantic and European Seas using this scheme.

The assimilation is specific problem in the North Atlantic, requiring *ad hoc* developments, due to the variety of scales, domain extension, geographic boundaries, and observing systems. Choices must be made to successfully develop an assimilation system from the research to the operational level: scientists, science managers and customers must be involved in the decision process.

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Short-term ocean prediction, with applications to the Atlantic and Mediterranean

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Current approaches to ocean prediction

There are currently two possible end-to-end perspectives for ocean prediction, involving different objectives and different technological requirements. The first one is long-term (seasonal, year to year, decadal) forecasting, which has obvious climatic and therefore commercial applications. The global climate, El Niño/Southern Oscillation predictions and investigations on the impact of the North Atlantic Oscillation are examples. This first perspective typically involves techniques to initialise a coupled ocean/atmosphere/ice model and the maintenance of a long-term monitoring network. The second perspective, the one considered here, is short-term ocean prediction (days to weeks). Here the applications are mostly coastal or regional, such as the prediction of biological marine parameters and coastal currents, or the prediction of the deeper acoustic structure of the ocean. The technology involved is classic sequential data assimilation in a hierarchy of generally high-resolution numerical models, coupled to or forced by atmospheric short-term and medium-term forecasting models. Data must be routinely and globally available in near real-time (NRT); therefore the primary data source is satellite measurements (altimetry, SST), completed by NRT in-situ observations such as XBTs available on global network systems.

The LEGOS Data Assimilation team in Toulouse is involved in a variety of large-scale science projects involving ocean forecasting (mostly short-term):

- The MERCATOR French operational high-resolution global ocean prediction project (Principal Investigator: P. Courtier).
- The CLIPPER French Atlantic high-resolution simulation project (Principal Investigator: C. Le Provost).
- The MFS project (Mediterranean Forecasting System), in particular the MFS Pilot Project (MFSPP) submitted as the phase 1 of the MFS to EU/MAST in October 1997 (Coordinator: N. Pinardi). This project is a EuroGOOS Test Case for the Mediterranean. Experimental Mediterranean forecasting is already going on in the framework of the MATER program.
- The GANES project (Global AssimilatioN applied to modelling of European Shelf seas) submitted to EU/CEO in October 1997 (Coordinator: K. Haines) – It is an application of the ongoing AGORA global data assimilation project to providing boundary conditions to regional/coastal modelling groups.

All those short-term prediction projects and others rely on a strategy involving a hierarchy of numerical models. At the top level, large-scale Ocean Prediction Systems (LSOPS) at intermediate to high resolution (1/6° to 1/12°) in forced and coupled mode are developed. A good example is the global OCCAM model used in part of the AGORA project, or the high-resolution model which will be used in MERCATOR. The LSOPS are develop in such a way as to:

- Assimilate altimetry, SST and other sensors in near-real-time
- Provide short-term forecasts of currents, temperature and salinity in the upper 1000m or so, including SST
- Provide initial and boundary conditions for Regional and Coastal Ocean Prediction Systems (RCOPS) which in turn will predict biochemical and physical variables needed for the regional and coastal applications.

In both the LSOPS and RCOPS, tools and diagnostic procedures are being defined in order to conduct impact studies and observing system simulation experiments. Of particular importance is the definition of short-term prediction skill diagnostics (such as the norm of the innovation vector for a Kalman filter for instance). The impact of near-real-time conditions on skill (NRT algorithms on altimetry data, use of atmospheric forecasts in

forced mode, etc.) must clearly be assessed if the system is to be used in real-time.

Finally, links are being developed between the large-scale / ocean physics / satellite data communities on one side and the regional/ coastal/ecological applications communities, in particular on nesting/boundary forcing issues (e.g. resolution, consistent physics). These links are to prompt technological transfers between the communities, for instance on data assimilation methodologies.

For the large-scale modeller and ocean forecaster in particular, the central scientific question is to know what are the main elements of a data assimilation system (various kinds of data, data quality, forcings, coupling, resolution, climatic drifts, etc.) which influence the forecast skill at the mesoscale and overall basin scale for the time scales of a few days to a few weeks. The question of the predictability of ocean phenomena has been addressed by various authors. For instance, Brasseur *et al.,* (1996) study the error growth and predictability in a North Atlantic quasigeostrophic model in which TOPEX/POSEIDON altimeter data are nudged. They find error variance doubling times of the order of three weeks. The influence of various data types on hindcasts and predictions is examined by Morrow and De Mey (1995) in a regional model assimilating data with the help of variational assimilation; they find that the improvement brought by the assimilation of local *in situ* data is kept by the model for up to two months, and clearly improves short-term forecasts.

The aforementioned projects make it possible to explore more "strategic" questions which will be useful for the design of future operational ocean systems, such as:

- What must be the resolution of the basin-scale model in the perspective to provide useful boundary conditions to regional models?
- Given a "minimal" but reasonable NRT data collection configuration : altimetry, SST, XBT profiles available on the GTS, 3-10 day atmospheric forecasts, are we very far from our objectives?
- If we need more data, do we know how to assimilate them?
- What is the tradeoff between NRT availability and accuracy of the data (and of atmospheric products)?

In the first place, low-cost but effective data assimilation methodologies must be implemented in the generally expensive high-resolution basin-scale models.

Data assimilation strategies

The size of oceanic data assimilation and short-term prediction problems is large (10^6-10^9) when compared to atmospheric configurations because of the much smaller spatial scales involved in mesoscale processes. Classic assimilation methods such as the Kalman filter cannot be directly applied. Therefore the order of the assimilation problems must be reduced. Two constraints must be considered:

1. The reduction of order must be efficient ()

2. Physical knowledge is needed since the errors in the resolved (corrected) subspace must be dynamically uncoupled (or weakly coupled) to the null space of the order-reduction transformation.

One first idea also used in meteorology is to simplify the state vector by projecting on a predetermined attractor, in such a way as to correct only part of the model physics with assimilation. For instance, a simpler control space can be defined for low-frequency, deep, open-ocean problems at mid-latitudes by correcting only the geostrophic, hydrostatic part, using rigid-lid physics (no free surface), and using exact or approximate conservation laws for properties, e.g. along isopycnal surfaces through assimilation. Another line of thought is to simplify or model the error covariances involved in methods such as the Kalman filter. This can be done by using a priori statistics (mostly on the vertical) or by projecting the errors (and therefore the "control space") onto predetermined directions. Examples (not all formalised) of order reduction are given in De Mey (1997). A promising order-reduction method is the isopycnal EOF method (Gavart and De Mey, 1997).

The team develops and uses a data assimilation code named SOFA (De Mey, 1994), interfaced with all of the team's numerical models (in particular OPA8 and MOM1). SOFA is a reduced-order optimal interpolation (ROOI) code based on simplifications of the Extended Kalman Filter (EKF). Classic OI is used in most weather prediction centers worldwide. A

schematic of the derivation of the SOFA scheme from the EKF is given below.

Step 1 : Project the stochastic forcing (order reduction)

- Define a linear projection operator **S** of rank $r<<n$ much smaller than the original rank n of the problem
- Project the innovation $\delta\mathbf{x}$ as $\delta\mathbf{w} = \mathbf{S}\delta\mathbf{x}$, assume no error in ker **S** (therefore the choice of **S** must make physical sense)
- Define the pseudoinverse transformation $\mathbf{S}^{-1}$ (with $\mathbf{SS}^{-1} = \mathbf{I}$) that will apply the stochastic forcing to the model space
- Rewrite the Kalman gain and EKF prediction equations in image space
  - The new observation operator writes $\mathbf{G} = \mathbf{HS}^{-1}$
  - The new forecast error covariance matrix writes $\mathbf{O}^f = \mathbf{SP}^f\mathbf{S}^T$
- The forecast is still produced by the non-approximated model

Step 2 : Simplify the Extended Kalman Filter formalism

- Parameterize the forecast error covariances as $\tilde{\mathbf{O}}^f = \mathbf{D}^{f\,1/2}\,\mathbf{C}\mathbf{D}^{f\,1/2}$
  - The diagonal matrix $\mathbf{D}^f$ contains the forecast variances
  - The correlation matrix **C** is predefined
- Rewrite ROOI Kalman gain (e.g. Ide *et al.*, 1997)

Up to now, SOFA has mostly been used to assimilate altimetry data into a variety of LSOPS-type ocean models. Tested choices for the projection operator with SOFA include in particular the vertical isopycnal/neutral-surface EOFs already mentioned (Gavart and De Mey, 1997) and the lifting/lowering method (Cooper and Haines, 1996). Tested choices for the prediction of the forecast variances include empirical schemes and empirical growth models (e.g. De Mey, 1994) and Monte-Carlo ensemble forecasting.

Global and Atlantic forecasting

The Team is conducting global and Atlantic data assimilation and forecasting within the European Union ENVIRONMENT/AGORA Program. In addition, a proposal to make LSOPS-type improved AGORA global and Atlantic fields available to regional modelling groups running RCOPS, named GANES, has been submitted to the EU CEO call in October 1997.

A medium-resolution rigid-lid primitive-equation Ocean General Circulation Model (OPA8 – Madec and Imbard, pers. comm., 1996) on a global grid is forced by reanalysed ECMWF winds and fluxes. The grid has an average resolution of 1.5°, higher in the Tropics. The model has TKE vertical turbulent diffusion, and a choice of isopycnal and Gent and McWilliams horizontal turbulent diffusion. Wind stress, heat fluxes and evaporation minus precipitation budget are derived from 6-hourly ECMWF reanalyses and operational analyses in 1990-1995. ECMWF heat fluxes are corrected with a feedback term using SST differences between the model and CAC analyses. A similar configuration with resolutions varying from 1/3° to 1/12° is run in the North Atlantic and the whole Atlantic within the French CLIPPER modelling project.

Comparison of the modelling results with TOPEX/POSEIDON altimetry and with available tide gauge data at various global locations is ongoing, in particular in order to select the processes which must be corrected for in the model via data assimilation. Comparison with T/P data shows a good agreement in the Tropics and in northern part of subtropical gyres. The main discrepancies in the global low resolution model are located near western boundary currents and in the Southern Ocean as expected.

Experiments in the global model are being conducted with the SOFA reduced-order optimal interpolation code assimilating TOPEX/POSEIDON altimeter data. The main purpose is to help correct the seasonal cycle of the model as well as to compensate the deficiencies in some meteorological forcings, in particular the operational analyses in the Southern hemisphere. Assimilation and forecasting experiments within the Atlantic higher-resolution model configurations within the CLIPPER and GANES projects are expected to occur in 1998.

Mediterranean forecasting

The Team has been and is involved in several EU-funded Mediterranean data programs, where it conducts data assimilation and forecasting experiments in both LSOPS and RCOPS: MAST/MERMAIDS, MAST/MATER, as well as the MAST/MFS project submitted last October.

A rigid-lid primitive-equation ocean model (MOM1) has been implemented at two horizontal and vertical resolutions: 1/4° / 19 levels, and 1/8° / 31 levels. It is forced in 1992-94 by ECMWF 6-hour operational analysis products (Benkiran and De Mey, pers. comm., 1997). The fluxes are of the interactive type, with May / Kondo parameterization. Custom wind stresses are derived from 10-meter winds. TOPEX/POSEIDON and ERS-1 altimetry assimilation is performed with SOFA projected onto vertical EOFs. A full dynamical validation of the 1/4° LSOPS including comparison with external data has been carried out as part of Benkiran's Ph.D. Thesis (pers. comm., 1996). In particular the 1/4° RMS difference sea-level anomaly from T/P is O(2cm) in 1993. The 1/8° system validation is ongoing. In addition to the general circulation, the simulations with and without data assimilation are able to reproduce the main water masses present in the Mediterranean, including the Modified Atlantic Water and Levantine Intermediate Water paths in the basin.

Optimal interpolation with T/P is carried out in 1993-94 in both versions of the LSOPS and does improve the forecasting capabilities of the systems, in particular in the 1/8° version. Runs with ERS-1 data in addition to T/P have also been carried out and increase the reliability of the currents and temperature structure in the coastal areas, because of the higher track resolution. Short-term assimilation projects include the implementation of variational multivariate OI with the SOFA code, in order to permit the additional assimilation of T/S profiles and currents from drifters.

A regional zoom of the Northern Balearic basin including the Gulf of Lyons and Ligurian current is being implemented as an RCOPS interfaced with the LSOPS. The zoom uses the POM free-surface code with isopycnal vertical co-ordinates and open eastern and southern boundaries. In the process of preparing for data assimilation, the Team is conducting Monte-Carlo experiments with the model in order to explore the structure of the forecast error covariances in the regional model.

The Team is a major player in the Mediterranean Forecasting System (MFS) project, whose Phase 1 MFS Pilot Project has been submitted to EU/MAST last fall. The overall MFS goal is "To explore, model, and quantify the potential predictability of the eco-system and physical system fluctuations from the overall basin scale to the coastal/shelf areas and for the time scales of weeks to months through the development and implementation of an automatic monitoring and a nowcasting/ forecasting modelling system, the latter called the Mediterranean Forecasting System as a whole." From a pre-operational standpoint, "MFS will show the feasibility of a Mediterranean operational system for predictions of currents and biochemical parameters in the overall basin and coastal/shelf areas and it will develop interfaces to user communities for dissemination of forecast results."

The MFS Pilot Project (MFSPP, 1998-2000) aims at conducting a real-time forecasting exercise in the whole Mediterranean in 2000; the main elements for this exercise will be a hierarchy of LSOPS and RCOPS incorporating real-time altimetry and SST, forecast meteorological products, Voluntary Observing Ship XBT lines, and data from an instrumented mooring. The real-time assimilation and forecasting system will produce 5- to 10-day basin-scale forecasts and will be based on a variational multivariate evolution of the SOFA code. In addition this phase will implement RCOPS nesting and ecosystem modelling in relevant coastal/shelf areas around the Mediterranean.

Acknowledgments

Part of the work described here has been funded by European Union shared cost actions, in particular MERMAIDS-II (MAS2-CT93-0055), MATER (MAS3-CT96-0051), and AGORA (ENV4-CT95-0113), and by Centre National de la Recherche Scientific support to P. De Mey.

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Session D: Data, technology and logistics

EuroGOOS customer surveys of civil operational forecast requirements in the Atlantic (Abstract)

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Operational oceanography already exists in the civilian sector to provide short-term forecasts of surface wave conditions, sea ice, sea level, tides, sea surface temperature, storm surges, and in more limited circumstances, algal blooms, surface currents, current profiles, sediment transport, and the transport of pollutants and oil spills. A range of specialist prediction services has been developed for naval surface ship and submarine operations. EuroGOOS has developed a fairly sophisticated customer survey technique to identify the oceanic variables and data products required in operational mode by different classes of customer. The survey identifies the priority marine variables, and the accuracy, spatial resolution, temporal resolution, geographical scale, mode of delivery, and latency of delivery that are required or are acceptable. The survey forms have been used in Greece, Italy, Netherlands, Spain and the UK. A survey was run in Denmark during winter 1997-98. A slightly adapted survey was conducted by the European Space Agency (ESA) in 1995, and by the SeaNet group in 1996. About 300 organisations and agencies in 10 countries have completed the questionnaire so far. Some organisations return 5-20 separate responses describing different requirements. The responses are entered into a computer data base. This presentation will extract conclusions from the survey relating to the open ocean and deep water data product requirements.

Monitoring the Benguela Upwelling System

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Two major new marine programmes are currently being prepared in conjunction with the Southern African Development Community (SADAC) Angola, Namibia and South Africa - to address regional environmental and fisheries concerns throughout the entire Benguela upwelling region.

The first of these programmes, the Benguela Environment Fisheries Interaction and Training (BENEFIT) programme is a ten year regional fisheries and environment initiative due to commence in 1998. It's primary goal is to develop a regional fisheries management capacity for the commercially important Sardine, Hake and Horse Mackerel stocks within Namibian and Angolan waters based on both stock assessment and environmental research. There is a strong emphasis on training and empowerment as well as developing infrastructure; all designed to stimulate research in fisheries and the environment in this region. Current funding for environmental research within BENEFIT stems largely from German support through the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) while Norway makes a substantial contribution to fisheries research through NORAD. Currently, fisheries and environmental project proposals are being considered for funding by GTZ and NORAD.

The second proposal is to launch a World Bank (GEF) funded Benguela Current Large Marine Ecosystem (BCLME) study (of 10 years or more) where the primary objective is that of "monitoring the health of the ocean". In this context, programme concerns are environmental issues that influence the functioning of the Benguela ecosystem. This includes, for example, the effects of short and longer term climate change (e.g. El Nino, ENSO, global warming), pollution (e.g. sediment loadings from offshore diamond mining activities) and land-ocean interactions resulting from human activities. The geographic boundaries of this programme are far more extensive than the BENEFIT programme which confines itself to the shelf system. The BCLME study is therefore free to consider processes occurring in the wider South Atlantic region that might affect the Benguela system, such as climatically induced changes in oceanic circulation patterns. The BCLME proposal is separate from the BENEFIT initiative, but it would nevertheless contribute to BENEFIT. The current situation with this programme proposal is that the GEF have set aside funding to develop a Strategic Action Plan between the three regional governments. This should be initiated early in 1998. Following that, the plan is to develop an environmental monitoring strategy to be adopted and running as early as 1999.

A wide-ranging environmental project proposal has been developed by Drs. Mike Lucas and Raymond Pollard for consideration by BENEFIT and the BCLME programmes. The project proposal has been developed in collaboration with partners in South Africa, Namibia and Angola and ties between SOC and GTZ funded institutes in Germany (Warnemunde) are now being sought also. It is hoped that by 1999, SOC will be significantly involved with research, training and monitoring activities in the Benguela system.

Dynamics of Thermohaline Circulation Variability: a new Long-Running Program in the Subpolar North Atlantic (Abstract)

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The overall objective of the Sonderforschungsbereich (SFB) 460 "Dynamics of thermohaline circulation variability" in its initial phase is a better understanding of the processes relating the variability of ocean-atmosphere interactions to variations in the formation and circulation of deep water masses in the subpolar North Atlantic.

Of particular interest are process studies on open-ocean convection and of overflows over the sills between Greenland, Iceland and Europe, and the relation of these processes to the variability of warm to cold water conversion on interannual to decadal time scales. A further important objective is the determination of the uptake of anthropogenic Carbon dioxide and its redistribution within the deep thermohaline circulation.

The SFB was established in July 1996 and had its first field phase in summer 1996 and summer 1997. Observation strategies, instrumentation used, and some preliminary results will be presented.

GODAE and MERCATOR, as stages in the development of an operational system

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In 1995, the French oceanographic community held two workshops to discuss the opportunity of taking joint steps to develop a simulation tool of the global ocean circulation, assimilating observation data under pre-operational constraints. The purpose was to gather skills among French laboratories to build together a common system useful to scientific, civilian, commercial and other applications.

In 1996, all the French institutes and agencies concerned with the development of oceanography decided to share the definition and the carrying out of such a system: they launched the MERCATOR project.

At the beginning of 1997, the project passed a major step by entering the feasibility phase: the agencies involved showed their clear intention of seeing MERCATOR going forward. These agencies are the Centre National d'Etudes Spatiales (CNES), the Centre National de la Recherche Scientifique (CNRS), the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), Météo-France, the Office de la Recherche Scientifique et Technique OutreMer (ORSTOM), and the Service Hydrographique et Océanographique de la Marine (SHOM). The focal point for the project is CERFACS (Centre Européen de Recherche et Formations Avancées en Calcul Scientifique), with J.C. André as executive secretary, and P. Courtier as project leader.

MERCATOR is a contribution to the Global Ocean Data Assimilation Experiment (GODAE) planned for the years 2003-2005.

Main goals of the MERCATOR project

MERCATOR will offer within the next 5 to 7 years a system able to:

- simulate the global oceanic circulation and assimilate satellite and *in situ* data, providing in real-time nowcasts and forecasts,
- be used in a pre-operational mode for, e.g., military and commercial applications,
- contribute to seasonal climate forecasting by providing initial conditions for coupled ocean/atmosphere models.

MERCATOR, as an operational tool, will serve the scientific community by providing climatology of ocean fields.

Three users identified

Seasonal prediction

The meteorological community is considering the operational implementation of seasonal prediction systems. The predictions rely on the integration of a coupled ocean atmosphere model. Initial conditions are required both for the atmosphere and the ocean over the whole globe. MERCATOR will provide the initial conditions for the ocean whereas the atmospheric data assimilation systems used in numerical weather forecasts will provide the ones for the atmosphere. It is foreseen that MERCATOR will be developed in collaboration with ECMWF, which is presently operating a seasonal prediction system in experimental mode.

Marine applications

The French Navy is presently operating an experimental data assimilation system for the Eastern Atlantic. Open ocean nowcasts and 15 to 30 day forecasts of the mesoscale dynamics are expected, with primary interest for the Atlantic and the Mediterranean Sea.

Coastal applications also need high resolution open ocean boundary conditions for coastal models.

Scientific applications

The MERCATOR system will be a useful tool for research activities. It will:

- provide a complete description of the ocean circulation, consistent with satellite and *insitu* data, atmospheric forcings and the

dynamics and thermodynamics of the ocean,
- allow a diagnostic description of the climatic evolution of the ocean,
- provide 3-D ocean transport fields for bio-geochemical studies,
- help to describe some dynamical and thermodynamical processes of the ocean, including those implying the mesoscale,
- help to analyse data from the WOCE and CLIVAR programs as well as from ERS, Topex/Poseidon, Jason and Met satellites.

MERCATOR and the future of oceanography

Mercator will help with the preparation of:

- new and appropriate oceanic observation network, a French contribution to GOOS,
- second-generation climate models.

MERCATOR strategy of development

MERCATOR is conducted under the specific rules of industrial development, in close collaboration with research laboratories. MERCATOR has three more scientifically-oriented components, taking benefit from already existing research projects: modelling, assimilation and data flow handling, and a fourth one dealing with system definition.

* The MODELLING component

The aim of this component is to develop a high resolution Ocean Global Circulation Model based on primitive equations. The basic code is OPA, developed initially by LODYC. At the time of GODAE, it is expected that the ocean model will have, at the global scale, a typical resolution of 1/12 of degree. In order to achieve this goal, three lines of development will be followed:

- **Global, low resolution:** the main priority is here to concentrate on the global aspect of the problem, and in particular in coupled ocean-atmosphere mode. MERCATOR will benefit from and rely on the effort made by the French research community in the field of climate simulations, and co-ordinated by the "groupe GASTON", with the use of the OASIS coupler developed by CERFACS.
- **Basin scale, high resolution:** it is currently developed within the CLIPPER project, which aims at simulating the Atlantic Ocean circulation at the resolution of 1/6 of a degree at the equator, with a mercator grid going up to 1/12 degree at high latitudes. CLIPPER is a scientific project issued from the WOCE community, and involves scientists from LPO (Brest), LEGI (Grenoble), LEGOS-GRGS (Toulouse) and LODYC (Paris).

- Coupling of the OGCM with very high resolution regional models.

* The ASSIMILATION component

The aim of this component is to develop a global assimilation scheme allowing near-real time operations. At least three assimilation schemes - simplified Kalman filtering, adaptative filtering and variational methods - are considered alone or in a combination, taking into account the outcome of recent data assimilation projects (e.g. the European AGORA project).

* The DATA FLOW HANDLING component

The aim of this component is to develop the sub-system which will provide to the model the initialization, forcing, assimilation and validation data sets, i.e. the gathering of the data needed to initialise the MERCATOR model, as well as, to a certain extent, the data needed to validate it, It will rely on international programmes: WOCE, TOGA, GOOS/GCOS, CLIVAR, GODAE.
The procedures implemented to provide assimilation and forcing data will have to bear near-real time and routine operation constraints:

- the implementation of the near-real time forcing data flow will mostly rely on the competencies of the French and European meteorological centres,
- the JASON or ENVISAT altimeter data will play an important role. The development of reliable methods to allow near-real time altimeter data acquisition and processing will mostly rely on the DUACS European project.

* The DRIVING unit

Considering that data assimilation methods are currently in fast evolution, it is necessary to allow for flexibility in the algorithms which can be

accommodated, as well as to offer various possibilities for future evolution. It can be shown that the main modern data assimilation methods use more or less the same operators or solvers. In order to fulfil the above required flexibility, the algebraic component of the data assimilation methods and the scientific content of the operators will be made independent: a generalised coupler PALM will solve the algebraic part, allowing the scientific content of the operators to evolve with the outputs of the research community.

Some steps towards operational oceanography

GODAE, as it is proposed to be planned, consists of three main components: the space segment, the in-situ segment and the modelling and data assimilation segment. MERCATOR is the French contribution to GODAE.

Space segment

France has already significantly contributed to the emergence of operational oceanography through investments in the international observing research programmes: main contributor to the ERS1/2 programmes and beyond ERS the partner of NASA in TOPEX/POSEIDON. France will implement together with NASA the forthcoming JASON. France is expected to be a main contributor of the space segment of Metop, a long term commitment of Europe for the measurement of sea surface temperature and surface momentum fluxes. Operational oceanography further requires a long term commitment for high precision altimetry, and therefore a follow-on of JASON1. Following the example of scatterometry and the transfers of the mission responsibility from the development agency ESA to the user agency Eumetsat, the emergence of operational oceanography will probably imply similar transfers.

In situ *observations*

France has contributed to TOGA and WOCE *in situ* experiments. The future contribution of France to the *in situ* part of GODAE is currently discussed in the CORIOLIS working group chaired by IFREMER. It could be along 4 actions which build on already existing or planned systems: XBT measurements, Lagrangian profilers, Eulerian profilers (to be developed), and moored and drifting instrumented buoys.

Modelling and Assimilation

The MERCATOR project is conducting the research and development effort in this area. In order to ensure the operational implementation of the system, two additional elements are required besides the MERCATOR present team: high performance computing and archiving facilities, and a dedicated team of engineers.

A Global Ocean Observing System Center at NOAA's Atlantic Oceanographic and Meteorological Laboratory

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National oceanic and Atmospheric Administration Atlantic Oceanographic and Meteorological Laboratory Miami, Florida

The National Oceanic and Atmospheric Administration (NOAA) of the United States Department of Commerce has inaugurated a Global Ocean Observing System (GOOS) Center at NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML). The initial objectives of the Center are (1) directed at co-ordinating NOAA's global and regional observing network efforts in order to maximise the quality and quantity of data available to users and (2) evaluating new observing methods for incorporation into existing networks.

NOAA's present global operations include AOML managed: (1) Volunteer Observing Ship (VOS) network that provides surface marine meteorological observations; (2) VGS network that provides upper ocean temperature data; and (3) surface drifter array that provides surface current, temperature and meteorological data. Regional networks include the TOGA TAO array, operated by NOAA's Pacific Marine Environmental Laboratory, that provides upper ocean and surface meteorological data in the tropical Pacific Ocean. Spatial coverage provided by the individual networks is provided on attached figures. The average number of observations provided by these systems per month is also summarised on an attached figure.

The data provided by these networks are used by NOAA's weather and climate forecast groups. Thus, the GOOS Center will direct it's efforts at the real-time, *in situ*, upper ocean and surface meteorological data needed by the NOAA forecasters. The Center activities will require that the operators of the individual networks continue to collect, quality control and disseminate their data.

Specific Center objectives include:

1. Ensure a continuous "pipeline" of data from sensor to user: Data pipelines will be established for each of the data networks. The pipelines will be "tapped" at various locations to ensure that data are flowing continuously. Breaks in the pipeline will be identified and corrected. The final taps will be placed at the modelling centres. This monitoring node will determine if data reaching the prediction Center are being used in the forecasts. If not, a determination will be made discriminating between problems with the observations versus problems with the assimilation/modelling methodology.

2. Evaluate and implement, after verification, new observing networks:

a) The ability to obtain and transmit high quality surface salinity data will be developed. Thermosalinograph (TSG) sensors will be placed on NOAA's research fleet to obtain in real-time, surface salinity data. Methods for sensor upkeep, data transmission and data quality control are being evaluated. Once these evaluations are completed, collection of TSG data from the U.S. research fleet and additional VOS will be implemented.

b) In the short term, expendable conductivity temperature depth (XCTD) probes will be used to obtain temperature and salinity profiles on a limited number of VOS. As is the case for the TSG observations, data transmission and quality control procedures must be developed for the XCTD data.

c) The ability to obtain temperature and salinity profiles from PALACE floats is under consideration using data from a large WOCE deployment in the North Atlantic.

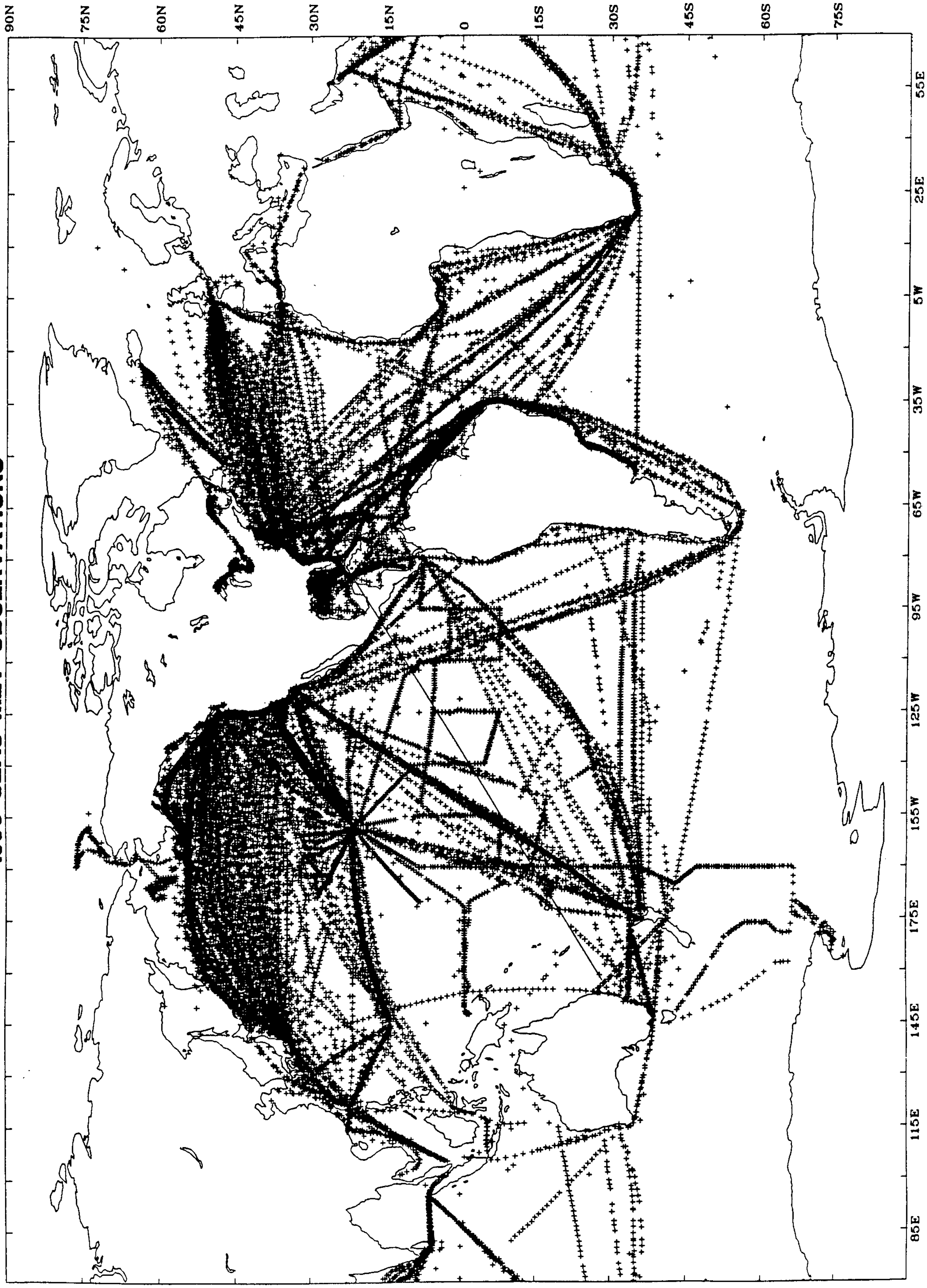
d) The ability to obtain surface wind observations from satellite tracked surface drifters is being evaluated through deployments in "hurricane alley" of the tropical and subtropical North Atlantic.

3. Develop new products that incorporate data from the diverse observing networks:

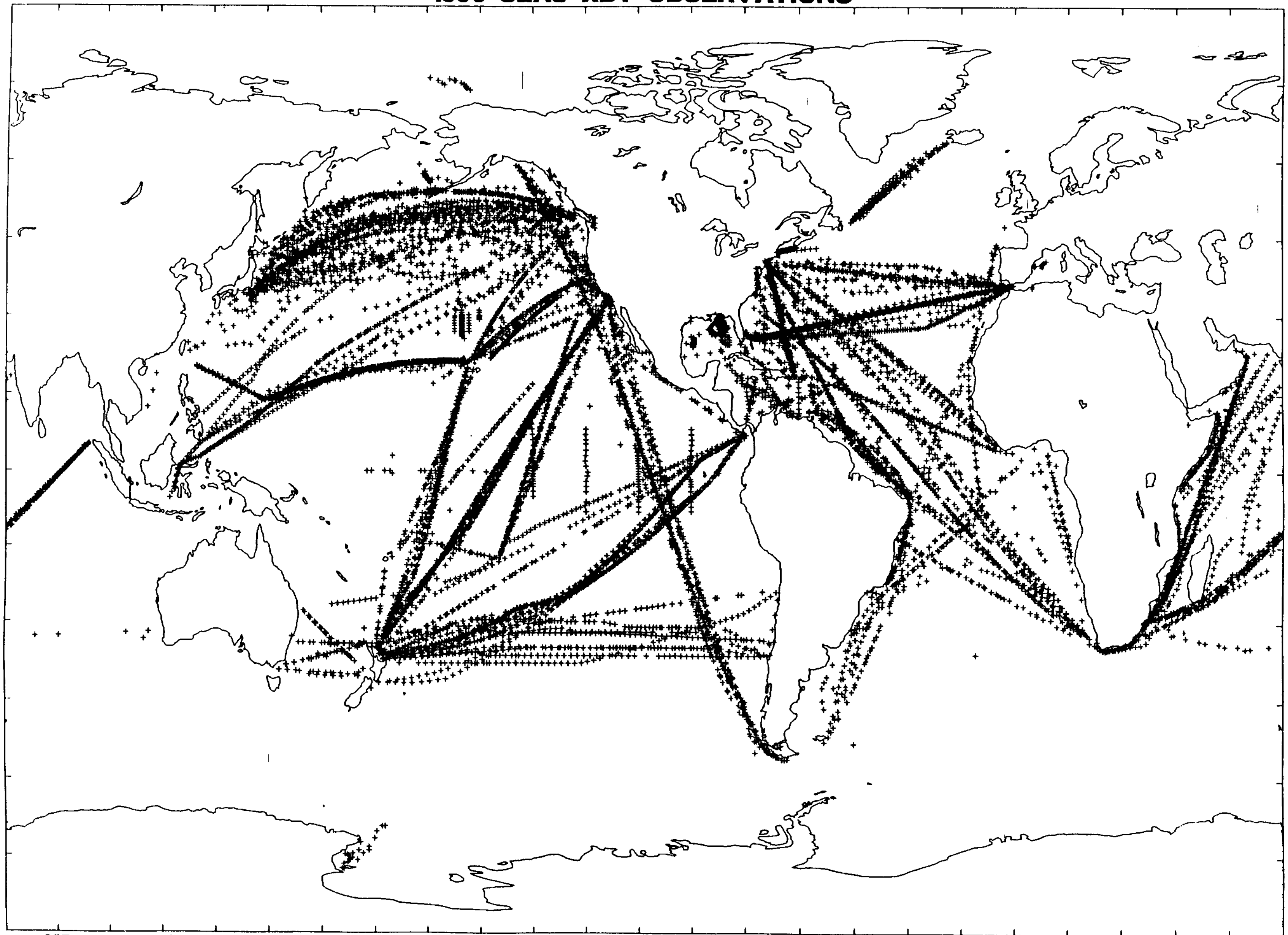
New products will be developed to provide a portrait of the characteristics of the upper ocean and surface atmosphere. The products will combine data from the diverse observing networks to define the state of the surface air/sea boundary layers.

The NOAA global observing networks provide considerable data in the Atlantic Ocean. Extensive co-ordination with any EuroGOOS effort in this basin is critical to ensure maximum benefits from the typically limited resources available to individual network operators. Historical precedence for this co-operation has been established through the WOCE program for instance. Within WOCE, bodies for co-ordinating VOS activities were established to maximise the data available from an expendable bathythermograph, upper ocean temperature data collection effort.

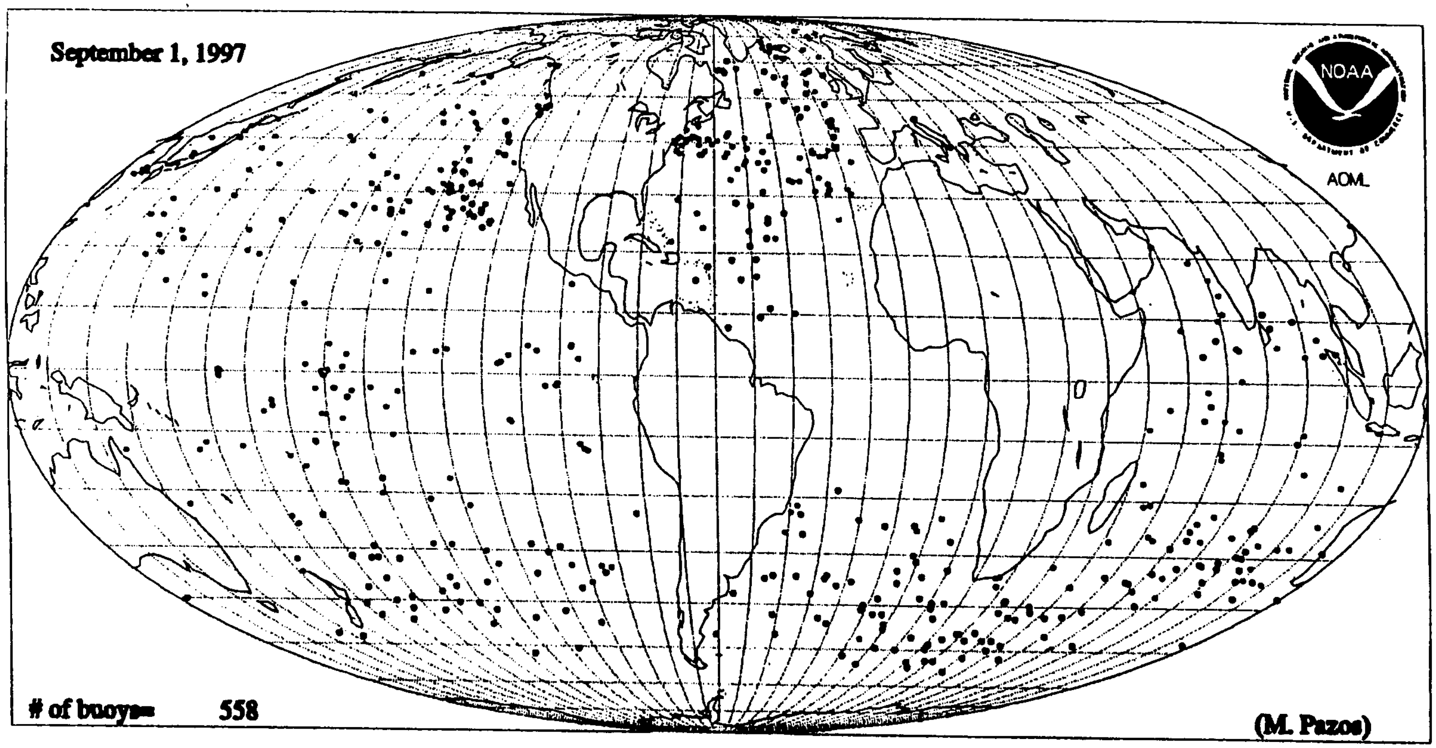
1996 SEAS MET OBSERVATIONS



1996 SEAS XBT OBSERVATIONS

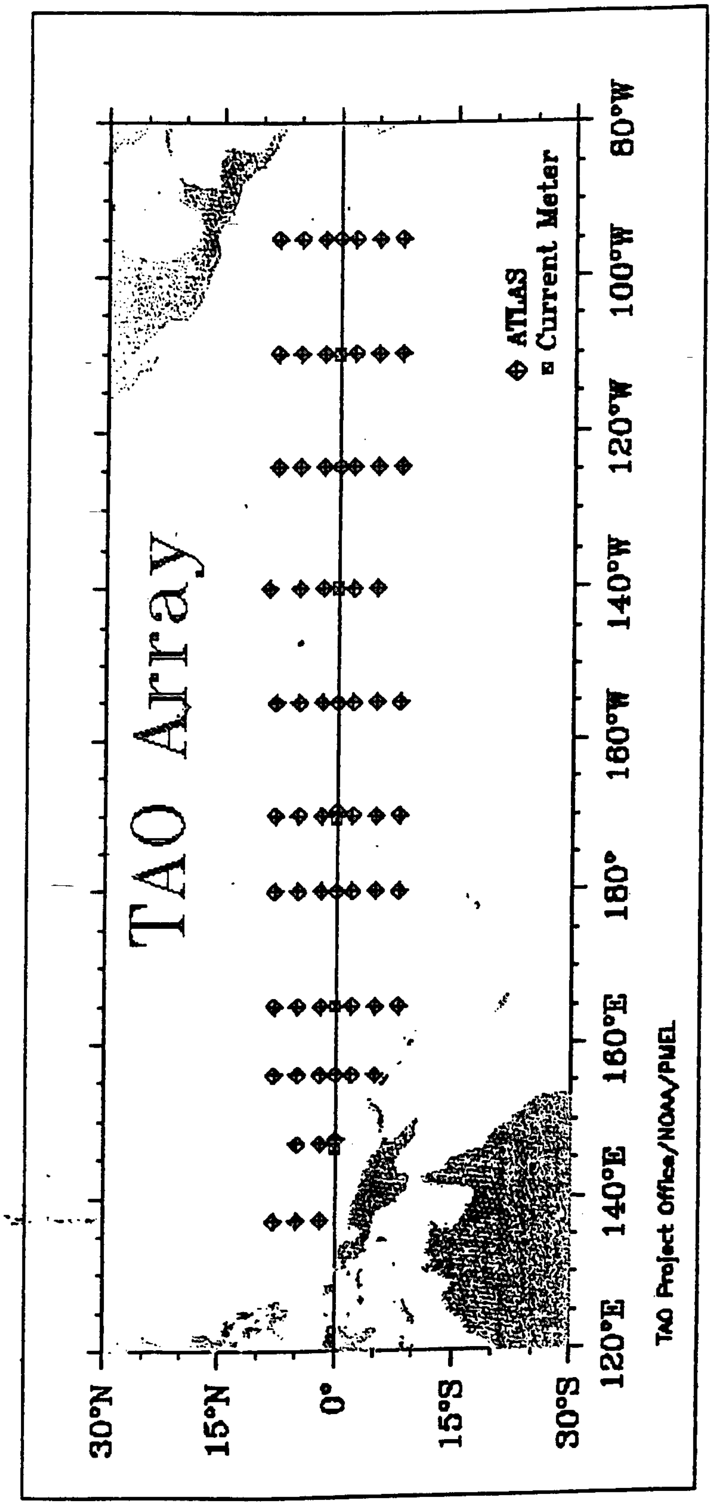


STATUS OF GLOBAL DRIFTER ARRAY



- SST ONLY
- SST AND BAROMETRIC PRESSURE
  SST AND SALINITY
- SST/SLP/WIND

GLOBAL DRIFTER PROGRAM
Peter Niiler
Mark Swenson


TAO Array
ATLAS
Current Meter
30°N
15°N
0°
15°S
30°S
120°E
140°E
160°E
180°
160°W
140°W
120°W
100°W
80°W
TAO Project Office/NOAA/PMEL

REAL-TIME OCEAN OBSERVATIONS AVAILABLE GLOBALLY BY MONTH

	NOAA +	OTHER (GLOBAL)	=	TOTAL/MONTH
UOT PROFILES				
XBT	1200	2700	=	3900
TAO	1650	------	=	1650
PALACE	51	650	=	701
SURF. CURRENTS				
DRIFTERS	4,000	2,000	=	6,000
SURFACE MET				
VOS	30,000	61,000	=	91,000
DRIFTERS(SST)	40,000	40,000	=	80,000
TAO	5,400	--------	=	5,400

Uses for Ocean Models - a Data Centre's Perspective

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Introduction

Ocean models and their output potentially provide a very useful source of additional data for end users. With the proliferation of desktop GIS systems, coupled with the advancement of processor power, the PC is a viable platform on which to base decision support systems and data products.

Ireland is a country with a significant area of interest in the Atlantic. The recent surge in activity along the Atlantic margin (particularly with regard to the oil exploration) has meant an increase in demand for data products. These products need not necessarily be models; they can also be datasets suitable for input into the end-user's relational database system or GIS. Such data products can be provided with model outputs, over time and space.

The Irish Marine Data Centre, through its data request service, is in a position to monitor trends of user requirements; the increase in demand for GIS-type data products is apparent.

Typical uses for model outputs:
- coupling with other models
- data products ("added value data")
- data for input into the end-users GIS or desktop Relational database
- data for end-users' decision support systems (may be a GIS/RDBMS)

Useful formats for data:
- Gridded data (useful for input into other models, analogous to Raster type data)
- Vector data (useful for GIS)
- Contoured data sets
- Region features
- Linear features
- Point features
- Feature attributes

Type of data required:
- Typical parameters (Temperature, Bathy, Salinity, Current Patterns, Wave climates, Sea States etc.)
- Metadata ("data quality", confidence)
- Spatial resolution (including geoid)
- Temporal resolution

Access to data:
- data products should be intuitive to use, requiring little or no need for manuals and documentation
- CD-ROM
- WWW/Internet
- Real time access

User profiles:
- Government
- Semi-state
- Private
- Research
- General Public

Conclusions

In summary, data output from models, particularly the Vector type data as discussed, has the potential to provide a very useful dataset for the use in Decision Support type systems, and "added value" data products, and provides a means to widen the user base considerably.

Acronyms

ADCP	Acoustic Doppler Current Profiler
ADCPPRED	A short-term current forecasting system
AFMIS	Advanced Fisheries Management Information System
AGORA	European Union global data assimilation project
ALACE	Autonomous Lagrangian Circulation Explorer
AO	Atlantic Oscillation
ATT	Atlantic Task Team (of EuroGOOS)
AUV	Autonomous Underwater Vehicle
AVHRR	Advanced Very High Resolution Radiometer
BENEFIT	Benguela Environment Fisheries Interaction and Training programme
BIOSYNOP	Biological Synoptic Ocean Prediction
BMRC	Bureau of Meteorology Research Centre, Australia
BT	Bathythermograph
CLIPPER	French Atlantic high-resolution simulation project
CLIVAR	Climate Variability and Predictability (of WCRP)
COADS	Comprehensive Ocean Air Data Set
CTD	Conductivity Temperature Depth
DAMEE-NAB	Data Assimilation and Model Evaluation Experiments - North Atlantic Basin
ECMWF	European Centre for Medium Term Weather Forecasting
EKF	Extended Kalman Filter
EnKF	Ensemble Kalman Filter
EOF	Empirical Orthogonal Function
EOS	Earth Observing System (NASA, USA)
ERS	European Remote Sensing Satellite
EU	European Union
EuroGOOS	European Global Ocean Observing System
FNMOC	Fleet Numerical Meteorology and Oceanography Center, USA
FOAM	Forecasting Ocean Atmosphere Model
FPSO	Floating Production, Storage and Offloading facilities
GANES	Global AssimilatioN applied to modelling of European Shelf seas
GCOS	Global Climate Observing System
GDEM	Generalized Digital Environmental Model
GEOSAT	Geodetic Satellite
GFDL	Geophysical Fluid Dynamics Laboratory (USA)
GLOBEC	Global Ecosystem Experiment
GODAE	Global Ocean Data Assimilation Experiment
GOOS	Global Ocean Observing System
GRIB	Gridded Binary
GTS	Global Telecommunication System
HOPS	Harvard Ocean Prediction System
IDOPT	Identification and Optimization of Systems in Physics and Environment
IO	Input/Output
IR	Infrared
JASON	Scientific panel (MITRE Corporation)
JGOFS	Joint Global Ocean Flux Study
LABL	Single-layer atmospheric boundary-layer model
LCU	Lightweight Command Unit
LSOPS	Large-scale Ocean Prediction Systems
MAST	Marine Science and Technology (DG-XII CEC)
MATER	European Union shared cost action

MCSST	Multichannel Sea Surface Temperatures
MERCATOR	French operational high-resolution global ocean prediction project
MERMAIDS	European Union shared cost action
MFS	Mediterranean Forecasting System
MFSPP	Mediterranean Forecasting System Pilot Project
MICOM	Miami Isopycnic Co-ordinate Ocean Model
MOCA	Modelisation de la Circulation Atlantique
MOM1	Rigid-lid primitive-equation ocean model
NAC	North Atlantic Current
NAO	North Atlantic Oscillation
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data and Information Service
NLOM	NRL Layered Ocean Model
NRL	Naval Research Laboratory
NRT	Near Real-time
NWP	Numerical Weather Prediction
OASIS	Observation at Several Interacting Scales
OCCAM	Ocean Circulation and Climate Advanced Modelling
OI	Optimal Interpolation
ONREUR	US Office of Naval Research in Europe
OSS	Observation Simulation and Sensitivity (experiment)
POM	Princeton Ocean Model
QG	Quasi-Geostrophic
RAFOS	Sound Fixing and Ranging Floats (a form of pop-up sub-surface float)
RCOPS	Regional and Coastal Ocean Prediction Systems
RIGADCP	GEOS software suite
RMS	Root Mean Squared
ROOI	Reduced-order optimal interpolation
ROV	Remote Operated Vehicle
SAWG	Science Advisory Working Group (of EuroGOOS)
SEEK	Singular Evolutive Extended Kalman
SEMAPHORE	A cruise
SIMAN	Simulation de l'Atlantique Nord
SOFA	Reduced-order optimal interpolation code
SOPRANE	Systeme d'Observation de la PRevision de l'Atlantique du Nord Est
SPEM	A model
SSH	Sea Surface Height
SST	Sea Surface Temperature
SWAFS	Shallow Water Analysis and Forecast System
TOGA	Tropical Ocean Global Atmosphere Experiment
TOPEX/POSEIDON	Joint US/French Ocean Topography Experiment
TPWG	Technology Plan Working Group (of EuroGOOS)
VOS	Volunteer Observing Ship
WAM	Advanced Wave Modelling
WOCE	World Ocean Circulation Experiment
WOCE-AIMS	WOCE Analysis, Interpretation, Modelling and Synthesis
WOCE-IPO	International Project Office of the World Ocean Circulation Experiment
XBT	Expendable Bathythermograph

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First published 1998

ISBN 0-904175-33-2

To be cited as:
Le Provost, C and N C Flemming (eds) (1998) "The EuroGOOS Atlantic Workshop Report", EuroGOOS Publication No. 9, Southampton Oceanography Centre, Southampton. ISBN 0-904175-33-2.

Cover picture

Large image: "A water perspective of Europe", courtesy of Swedish Meteorological and Hydrological Institute. The white lines show the watershed boundaries between the different catchment areas flowing into the regional seas of Europe.

Inset image: Height of the sea surface in the north Atlantic and Arctic simulated by the OCCAM global ocean model, courtesy of David Webb, James Rennell Division, Southampton Oceanography Centre.